In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institution shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, or, in his absence, by the dean of the Graduate Division when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

AN

ELECTRONIC RECORDING

UROFLOWMETER

A THESIS

Presented to

The Faculty of the Graduate Division

by

David James Bryant

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Electrical Engineering

Georgia Institute of Technology

June, 1964

AN

ELECTRONIC RECORDING

UROFLOWMETER

Approved:

Chairm

Date approved by Chairman: June 10-64

ACKNOWLEDGMENTS

The development of this electronic recording uroflowmeter was made possible by the financial support and patience of Charles Eberhart, M.D., and through the use of the facilities provided by the Engineering Experiment Station of the Georgia Institute of Technology. The assistance of Ralph Ragan and the assistance and patience of Dr. Frank O. Nottingham of the School of Electrical Engineering is gratefully acknowledged.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SUMMARY

An electronic recording uroflowmeter was designed and constructed to record instantaneous urine flow patterns on a strip-chart recorder. It has a linear dynamic range of zero to fifty milliliters per second and utilizes a new electronic flow transducer designed by the author for low open-channel flow rates. To the patient it has the appearance of a small white commode and is used similarly after pressing a switch to start the recorder. No training is required of the patient and the uroflowgram (urine-flow pattern) can be made in complete privacy.

Urine flowing through a one-half inch (inside diameter) polystyrene tube alters the parameters of a specially constructed 150 megacycle per second (mc) transformer to cause the detected output voltage of the transformer secondary to vary with urine flow. A double modulation procedure is used and critical radio-frequency (rf) and direct current (dc) amplifier stages are avoided. After amplification in conventional audio amplifier stages, the signal is rectified and processed through a non-linear stage to operate a remotely located strip-chart recorder. The recorder provides a linear easily read, permanent record of urine flow (ml/sec) versus time; a paper speed of 3/8 inch per second provides a record of perhaps 10-15 inches for the average adult patient.

Overall error can be easily corrected by untrained personnel to about ± 2 ml/sec. As recorded there is a possible error of as

much as ten per cent of the reading, depending upon the amount of salts present in the urine. The device is portable and compact and is suitable for field operation. This uroflowmeter will allow gathering of data on urine-flow characteristics on men, women and children under perfectly normal conditions. The flow transducer is essentially a two-phase analyzer (air and fluid) and could be readily adapted to other uses by varying the mechanical arrangement.

CHAPTER I

INTRODUCTION

A recording uroflowmeter is defined as a device which automatically plots a graph (referred to as a uroflowgram) of urine flow versus time. Many urologists feel that an accurate uroflowgram may be an important diagnostic aid which will help furnish insight into operation of the urinary tract under influence of various diseases and disorders.

> Pediatricians and urologists have become increasingly aware that bladder-neck obstruction is often implicated in recurring urinary infections and in progressive renal disease in children. In the past, diagnosis of this disease has depended upon recognition of gross destructive changes in the urinary tract ..." [1].*

Children generally are difficult to diagnose for minor urinary infections; also, many adults become somewhat adapted to urinary infections and malfunctions of the bladder which are amenable to cure without surgery if detected early. An accurate uroflowgram may take its place in history alongside other diagnostic tests such as blood cell count, tuberculosis test, and electrocardiagraph if a portable, easily operated, and accurate instrument is available for general use. It is quite probable that an abnormal uroflowgram may never serve as irrefutable evidence of disorder, but many urologists feel that as an aid to diagnosis it would be most helpful. It may also be used in

---

* Numbers in the brackets refer to references listed in the Bibliography.

mass health tests, such as occur upon entrance to the Georgia Institute of Technology and the Armed Services of the United States, to indicate persons with possible disorders who should be checked more completely.

Experience has shown [2] that this particular test of recording the urine flow characteristics should be done under as nearly natural conditions as possible, i.e., with no observers, in order to obtain the most representative data. This requires that any instrument for this purpose be capable of operation by the patient (or remotely by the urologist's assistant) and present a benign appearance.

The electronic recording uroflowmeter described here has been designed with these particular aspects of the measurement problem as an unwavering requirement.

CHAPTER II

BACKGROUND

Early Theories and Need

"The observation that the size and force of the urinary stream are diminished in certain urologic conditions dates back well over one hundred years" [3]. In 1932, urologists [4] observed a definite correlation between the maximum distance a man could eject urine and certain urinary disorders.

Attempts have been made to devise a mechanical model of the bladder and lower urinary tract to investigate possible causes of decreased voiding rate and serve as an additional diagnostic aid to the urologist by correlating voiding patterns and induced problems in the mechanical model. The model showed many early theories to be incomplete and the need for establishing the normal flow pattern (and rate) was recognized. The practiced eye of the urologist, perhaps aided by a stop-watch, served as the principal reliable instrument for many years although some quite serious drawbacks in this method were inherent, as noted in Chapter III of this thesis. Over the years, general knowledge of urine flow patterns and rates under certain conditions increased significantly, but the need for an accurate measuring instrument of urine flow patterns and rates remained essentially unfulfilled until after World War II.

General Urine Flow Characteristics

Observations over many years have yielded much data on urine flow characteristics, and many papers on observations of the urine flow characteristics of both adults and children have been published [5,6,7,8,9]. The paper by Kaufmann [10] summarizes urine flow characteristics as 26-44 milliliters per second (ml/sec) and 13-26 ml/sec as the normal maximums for adults and children respectively. Some general flow patterns are depicted diagrammatically in Figure 1, with flow rate (ml/sec) as ordinate and time (sec) as abscissa.

The characteristics of voiding patterns in the normal male are covered quite thoroughly by Bodo von Garrelts [11], who also devised what appears to this writer to be a quite sophisticated device, discussed in Chapter III, for measuring urine flow patterns. Von Garrelts' device used a strip-chart recorder speed of about 1 mm/sec, together with a time-constant of one-quarter second, to give what appears to be the first recorded information on transients that occur during micturition. The significance of transients other than stopping or starting is apparently not yet established, but it appears that information other than average voiding rate, length of the micturition period, maximum flow rate, and total volume voided are significant; i.e., reduction of uroflowgrams to a table for analyses may be misleading in that the shape of the pattern may prove significant, indicating good transient response is desirable.

The information generally sought about urine flow patterns is contained in graphs of urine flow rate versus time, but urine flow rate versus accumulated volume voided may also be significant.

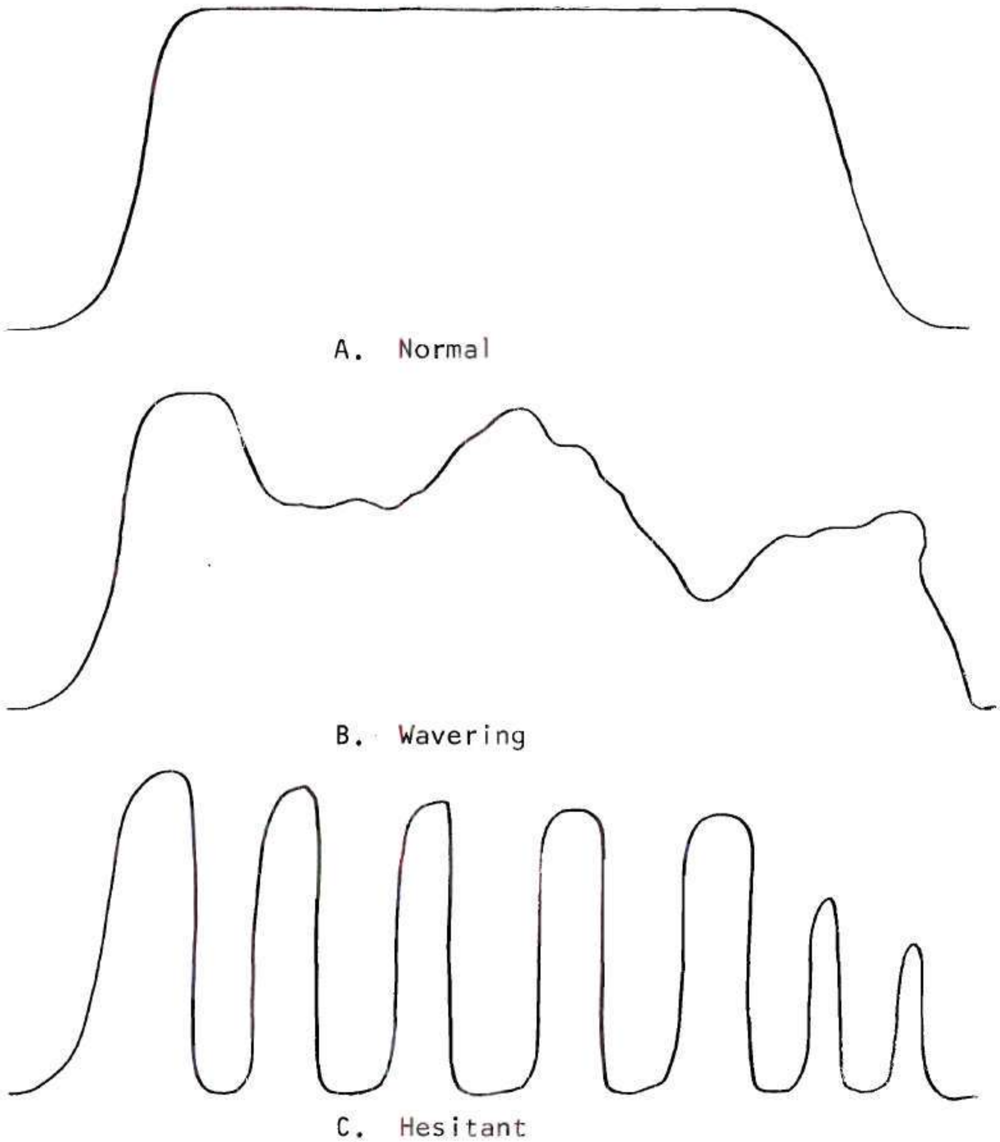


Figure 1

General Urine Flow Patterns

Reduction of the former to the latter is quite straightforward and could be implemented automatically on the device described in this thesis if it appears desirable when sufficient information becomes available. Urine-flow characteristics for specific groups and classification of types of patterns have not yet been established under natural voiding conditions, but will certainly follow in the next few years if present interest in uroflowgrams continues. Enough information on urine flow rate versus time exists to establish desired characteristics for a suitable uroflowmeter; desired characteristics are covered in Chapter III.

The length of the voiding period [2] varies widely, but a normal average of twenty seconds can be used for equipment design purposes. If the recording device -- a standard, commercial strip-chart recorder, for instance -- uses a uniform chart speed of about one-half inch per second, the average uroflowgram would be about 10-15 inches long. This is adequate for the purposes the uroflowgram will serve.

It is immediately apparent that the instantaneous flow rate is the time derivative of the volume voided, and this is the basis of operation of most known urine-flow recording instruments to date, excluding the device described in this thesis.

Early Instruments

Several recording devices [3,10,12,13] have been described in the literature, but only the Kaufman device [10] is commercially available as a recording uroflowmeter; it is manufactured by the

Charles Meriam Company, Los Angeles. C. R. Bard, Inc., Summit, New Jersey, markets a non-recording, hydrodynamically operated device invented by W. M. Drake, Jr. which gives an approximate indication of the flow pattern and maximum flow rate, but it has a very serious drawback in that an observer must be present during micturition. It is highly desirable that the patient be alone while information is being gathered about urine flow characteristics as some persons have a "bashful bladder"* and their urine-flow pattern with an observer is not representative of the normal situation. Also, Drake's device depends on the observer's facility with a stop-watch for much of the data.

One report [14] had this to say recently about attempts to gather data, using existing instrumentation, on urine flow patterns of little girls:

> Attempts to use the available flow meters (Drake [1948,1954] and Kaufman [1957]) with the usually apprehensive little girl frustrate both the patient and the doctor. It is obvious to the urologist working with children, or with women for that matter, that effective and reliable measurement of urinary flow can only be done by a device benign enough in appearance not to cause voiding inhibitions.

Following is a brief chronological discussion of various methods and devices that have been used in the past:

a. Prior to 1932, various urologists had noted the correlation between urine flow patterns and various urological disorders. The primary technique used was simply visual observation of the

---

* A term used by urologists in referring to those individuals who have difficulty urinating in the presence of others.

micturition of the patient and noting the salient aspects of the urine flow pattern. Comments in various articles indicated some mechanical device may have been used for assistance, but no descriptions are given.

b. In 1932, a group of urologists noted a correlation between the distance a man could urinate and bladder neck obstructions [4]. This report apparently was the first attempt to attach numbers and definite characteristics to the voiding pattern. Apparently no instrumentation was used.

c. In 1940, a Japanese writer reported the use of a weir-type device in measurement of urine flow [15]. The writer indicated there was not much future in urine flow measurements as a diagnostic aid. Perhaps his crude device misled him.

d. W. M. Drake, Jr., devised the first recording uroflowmeter from miscellaneous mechanical parts [3]. The principal of operation was quite simple: the urine is collected in a container, mechanically weighed by operating an attached lever which inscribes the instantaneous accumulated weight (or volume) on a rotating paper-covered cylinder. The information immediately available from the record is accumulated volume versus time. To find the flow rate at any time, the operator must manually determine the slope (which is the time derivative of accumulated volume) of the curve. The flow must remain steady for a few seconds in order to determine the slope reliably; thus transient observance is poor.

e. In 1954, Drake reported on another device which he had devised, apparently at the suggestion of D. M. Davis [8]. This device is operated by the dynamics of the fluid and, when coupled with the use of an observer with a stop-watch, gives some information on average flow rate, but not on transients. The urine is collected in a tapered, terminated tube which has holes spaced accurately from the bottom or terminated end. Depending upon available flow rate, the holes in the tube emit streams which are collected individually. The hole furtherest from the bottom indicates maximum flow; the others contribute some information to the observer.

f. A sophistocated device which gave the first direct recording of urine flow rate was described by von Garrelts in 1956 [12]. This device also weighed the urine as collected, but accomplished this electronically by use of a strain-gage bridge. The time derivative of the instantaneous volume was also taken through operational amplifier circuits and the output, which is proportional to flow rate, was coupled to a uniformly driven (paper speed of 1 mm/sec) strip-chart recorder to give a urine-flow versus time record. This device has several drawbacks which appear to limit its use, including complexity of calibration, drift, fairly critical circuitry and poor transient response.

g. Kaufman [10], in conjunction with some associates, improved significantly on the prototype model of Drake [3] and the instrument was placed in commercial use and is now available. It is still necessary to manually take the derivative of a graph to determine flow rate.

h. Scott and McIlhaney devised a funnel, cylinder, strain-gage manometer and associated strip-chart recorder to record accumulated volume versus time [16]. The chart from this device was similar to Kaufman's [10] and similar treatment was required for processing. Urine volumes in excess of 100 cc were required for accuracy. Since manual processing of the output data is required to obtain urine-flow patterns from volume versus time graphs, this type of instrument is, at most, semi-automatic. Kaufman [10] specifically states that he makes no claims for accuracy or precision for his device although he states that it is repeatable (but does not define this term).

For determining the slope of a volume versus time graph with any repeatability, a reasonably long interval of constant flow must elapse. Kaufman [10] stated that repeatable results are obtainable only if the total volume of urine voided exceeded 150 milliliters but Stewart [2] found this somewhat optimistic and required 200 mililiters minimum, stating that "flow rates vary tremendously and are not reliable" for smaller quantities. A moment's reflection will indicate the seriousness of the problem to a small child of accumulating in excess of a half-pint in a small bladder.

Urologists sometimes fill the bladder with a sterile liquid by means of a small tube (catheter) for repeated study of urine flow. Stewart [2] also found that "catheterization may alter the subsequent voided flow rate in either direction, and from a practical standpoint one simply cannot wait for all patients to accumulate over 200 cc in the bladder so as to void prior to catheterization."

i. In 1962, Holm [17] described an instrument which operated on the principle that the volume of urine passed per unit time displaced a corresponding volume of air from a container if the liquid input-tube has its outlet submerged, and a small tube is used to meter air flow from the container. Holm used a standard rotameter (a ball that rises in a clear tube with air flow) to visually take periodic readings during the urination period.

j. Cardus, et al., converted an electromagnetic blood flowmeter to devise a method for urine flow measurements [13]. The transducer is a Medicon Microflo electromagnetic blood flowmeter, gated sine-wave type, model K-2000. A small approximately U shaped tube was formed and filled with saline solution. The transducer is placed on the short end of the U while urine enters on the long end. The transducer measures, essentially, flow of the liquid as the short end overflows. The major disadvantage to this type of instrument for everyday use is that the urine which flows through the device is contaminated with a foreign substance, and devices of this type are relatively expensive. The authors claim excellent frequency response and error less than five per cent and that the device is insensitive to urine composition.

Search for a Transducer

After defining the problem, a general search [18,19] was made for complete instruments in use in industry or laboratory which could be adapted for use as a suitable uroflowmeter. The results were negative. The search then shifted to looking only for a transducer with desirable characteristics for converting open-channel flow to an electrical signal. More than twenty companies -- all well-known in this particular field of measurement -- were queried as to the availability of a desirable transducer. Again the results were negative. Next a search was made of the literature on flow transducers [20]. Of the many and varied types extant, none appeared to have the characteristics needed to solve the problem at hand. The electromagnetic flowmeter used for blood flow measurements was considered and rejected because of urine contamination by the priming fluid. Only one device* seemed to offer much: it was not designed for open-channel flow but appeared to be adaptable. However, a manufacturer's list price for the transducer alone -- it operates essentially as a thermistor bridge -- was $750 and this was deemed too expensive for the type of instrument needed, especially considering that it might not do the job. At this point, Thomas A. Edison's motto, "There's a way to do it better - Find it," seemed apropos.

The problem became, then, one of not only constructing an instrument, but devising the basic means by which the instrument operates, i.e., designing a new electronic flow transducer for open-channel flow of liquids. The new** transducer operates on a basic principle shared by no other flow transducer. It may be a signifi-

* Model 59 Electric Flowmeter, mfr.: Thermal Instrument Co., P.O. Box 72, Cheltenham (Philadelphia), Pennsylvania

** The writer had a preliminary patent search made by a local patent attorney and no obvious conflicting claims were discovered.

cant contribution toward the measurement of low instantaneous flow rates down to the point where a stream breaks into drops -- then it will give an electrical pulse out for each drop. The transducer will give the desired characteristics (see Chapter III) when utilized in a suitable mechanical set-up with appropriate electronic circuitry. The output can be made to vary approximately linearly with input flow up to 50 ml/sec (see Figure 2). Sensitivity to transients (see Figure 3) far surpasses the ability of any liquid in open-channel flow to change flow rate -- thus all transients will be faithfully reproduced. The rise and fall time shown in Figure 3 is caused completely by mechanical considerations. In measuring urine flow, the initial velocity of urine from the patient is carefully removed and replaced by a velocity due to gravity alone; this process, detailed in the mechanical description of the instrument in Chapter III, leaves adequate transient response for changes in urine flow patterns.

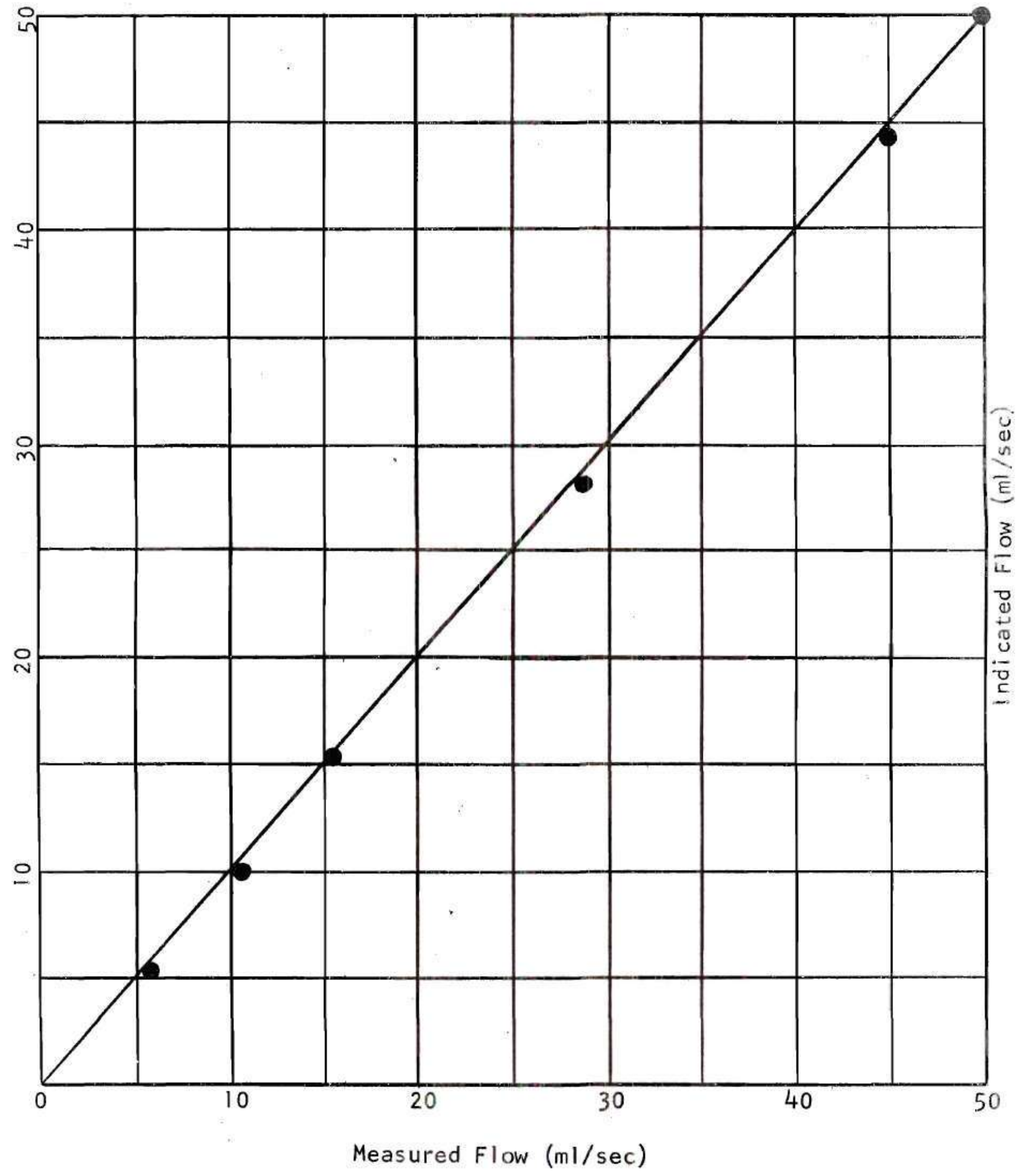


Figure 2

Input-Output Characteristics

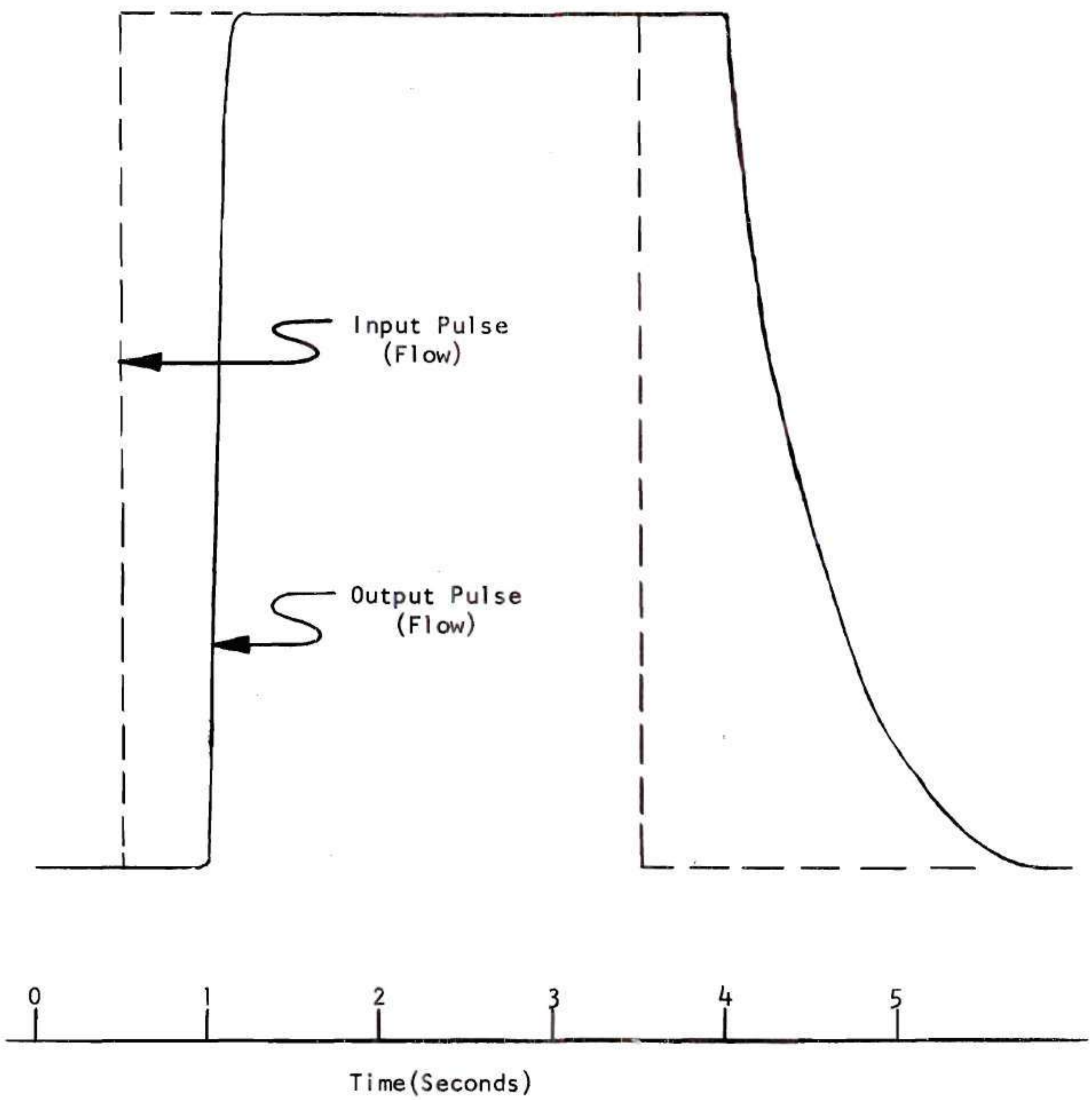


Figure 3. Transient Response

CHAPTER III

DESIGN OF THE INSTRUMENT

Design Philosophy

After many false starts, a tentative design for a transducer was determined and the design of the complete instrument was begun. It was necessary to integrate the transducer into a desirable mechanical arrangement for proper operation of the total instrument, as mechanical considerations are almost as important as electrical considerations in the instrument. A blending of the mechanical design of the flow channel and the electrical characteristics of the transducer was effected to realize the desired goal insofar as dynamic range, linearity and sensitivity to transients were concerned.

The design of an instrument of this type must necessarily involve compromises; hence it was decided to follow Sir Robert Watson-Watt's "cult of the third best: The best never comes and the second best comes too late." An approach (block diagram form) was formulated from the early data and was followed as closely as possible throughout the entirety of the lengthy design, construction and testing of the instrument. If it became apparent that a new approach would give more optimum results but the original approach was adequate, the original approach was followed. Recommendations for a newer and probably more optimum instrument for the purpose are given in Chapter V. The major purpose of the instrument described here is to demonstrate the feasibility of the principle --

this has been accomplished: one can accurately monitor the urine flow of individuals and record all significant transients that occur during micturition.

Desired Characteristics

The desired characteristics for an electronic recording uroflowmeter were discussed generally by the writer with a local urologist (for whom the instrument was primarily developed) and the following characteristics were deemed generally desirable:

1. A chart from a strip-chart recorder should be available for each urination period of each individual patient. The chart should have rectangular coordinates with the abscissa as time in seconds, the ordinate indicating flow-rate from zero to fifty (50) milliliters per second (ml/sec).

2. For ease of analysis, the chart should be 5-10 inches wide and approximately 10-15 inches long (this would depend upon the length of the urination period as the chart speed must necessarily be linear with time). The average length of the urination period is about 20 seconds for adults so a desirable chart speed is about one-half inch per second.

3. The instrument should have a dynamic range of 0-50 ml/sec with a linear input-output relationship. The flow-rate indicated should be insensitive to the composition of the urine (or fluid, as urologists often inject fluid into the bladder of a patient for observing and studying the operation of the bladder and associated organs under known conditions).

4. Faithful reproduction of transients with good repeatability and accuracy was desired. The limitations here were not stringent and no specific requirements were determined; however, the writer determined that $\frac{1}{4}$ to $\frac{1}{2}$ second rise time*, 1 to 2 ml/sec repeatability error, and an accuracy of five per cent (full scale) was desirable for confidence in the data from an engineering standpoint.

5. Simplicity of operation was highly desirable. It was a major objective to build an instrument that could be used by any patient unassisted and completely operated by an untrained (in electronics) nurse's aid.

6. The instrument should be moderately priced with safe and trouble-free operation. Even the remotest possibility that one could get shocked must be precluded by the design of the instrument.

It was felt that an instrument with these characteristics would, for the first time, give the urologist a precise record of the urine-flow characteristics of a patient under as nearly natural conditions as possible.

Obtainable Characteristics

The obtainable characteristics for the instrument were determined by making a reasonable effort to realize the desired characteristics and accepting compromises considering the time and financial

---

* defined as the time required for the output to change from 10 to 90 per cent of its final value with a step input 21 .

resources available. As development of the instrument progressed, the inevitable compromises between desired ideal performance and obtainable performance were made in order to complete the development project. The continuous intent was to develop an instrument that would do an adequate job for the task assigned. To this end, for example, a plan to have the strip-chart recorder operated by a fluid-operated switch, i.e., automatically turn on when urine first began to flow and turn off when it ceased, was abandoned as an added unnecessary complexity. Instead, a much simpler hand-held push-button switch is used.

Some significant points are:

1. The paper speed (hence the time per division) of the strip-chart recorder was fixed at 0.375 inches per second rather than the previously set 0.5 inches per second when an otherwise desirable recorder was found to be available at a modest price.* Usable chart width is 5 inches, a desirable width.

2. Complete freedom of fluid composition without appreciable change in indicated flow was not obtainable with the transducer as incorporated in the instrument discussed here. However, the indicated flow can be corrected by multiplying by a correction factor which is readily determined by inverting a small (50 or 100 ml) vial of sample urine and allowing it to run through the instrument and noting the maximum reading attained on the recorder. A scale factor is then determined depending upon whether the indicated maximum

---

* Esterline-Angus Recording Ammeter, 0-1 ma dc, Model AW

reading is greater or less than 25 ml/sec, say X. If X is greater than 25, the scale factor is 25/X; if X is less than 25, the scale factor is X/25. Determination of scale factor can be determined after the uroflowgram is taken and does not interfere with desired operation. The scale is set to give the correct reading for the solution used by the urologist when artificially (by use of a catheter passed through the urethra) filling the bladder to study its operation. The development of the transducer used in the instrument has pointed the way to a transducer, as noted in Chapter V, which will eliminate this minor inconvenience and give the correct flow indication independent of urine composition.

3. Some integration (smoothing) of transients occurs in the mechanical arrangement for the flow-channel, but it is acceptable and adequate response to transients is attained. The writer had, at the outset, no training or experience in hydrodynamics. This proved to be the most difficult portion of the construction and probably could be improved significantly.

4. The electronics circuitry for the instrument was designed conservatively and long and trouble-free operation is expected, depending upon the actual operating hours per day. The flow-channel is completely isolated from any voltage and for added safety, all metal parts are grounded using the National Electrical Manufacturers Association three prong grounding plug for a-c power input. As an added margin, the instrument was certified to be safe by a Registered Professional Engineer.

Overall Operation Of The Instrument

The overall operation of the instrument is outlined in block diagram form in Figure 4 and schematically in Figure 5. V1 is a 5 kc oscillator; V1A is also used as a plate modulator for V2. V2A is a 75 mc oscillator which is nominally 75% modulated with the 5 kc signal by V1A. V2B serves as a frequency doubler and driver for the flow transducer T2. The voltage induced in the secondary is a 150 mc signal whose amplitude varaes with the amount of fluid in the transformer core. Since the fluid is moving through at a controlled rate, the output varies with flow. V3 and its associated filter R4 and C6 rectify and filter the 150 mc signal and the output to V4A is a 5 kc signal at the millivolt level which varies with flow. The 5 kc signal is amplified by V4 and V5A and rectified by the diode-connected triode V5B. After filtering by C17 and R23, the output to V6B is a dc signal which varies with flow. V6 is a differential cathode follower with the output taken between pins 3 and 8. During quiescent conditions, the output is set to zero by varying the potential at V6A, pin 2, with Zero Adjust R30 on the Control Panel. The output current flows through non-linear elements D1-D4, Span Adjust R32 and the 1500-ohm recorder movement. The non-linear elements cause the current flow through the recorder movement to vary linearly with flow. Hand Switch S2 is used to start and stop the chart paper of the recorder as desired, either by the patient or by the urologist's assistant.

Power is supplied to the instrument through P2, a NEMA 3-prong grounding plug. On-off switch S1 controls power to the in-

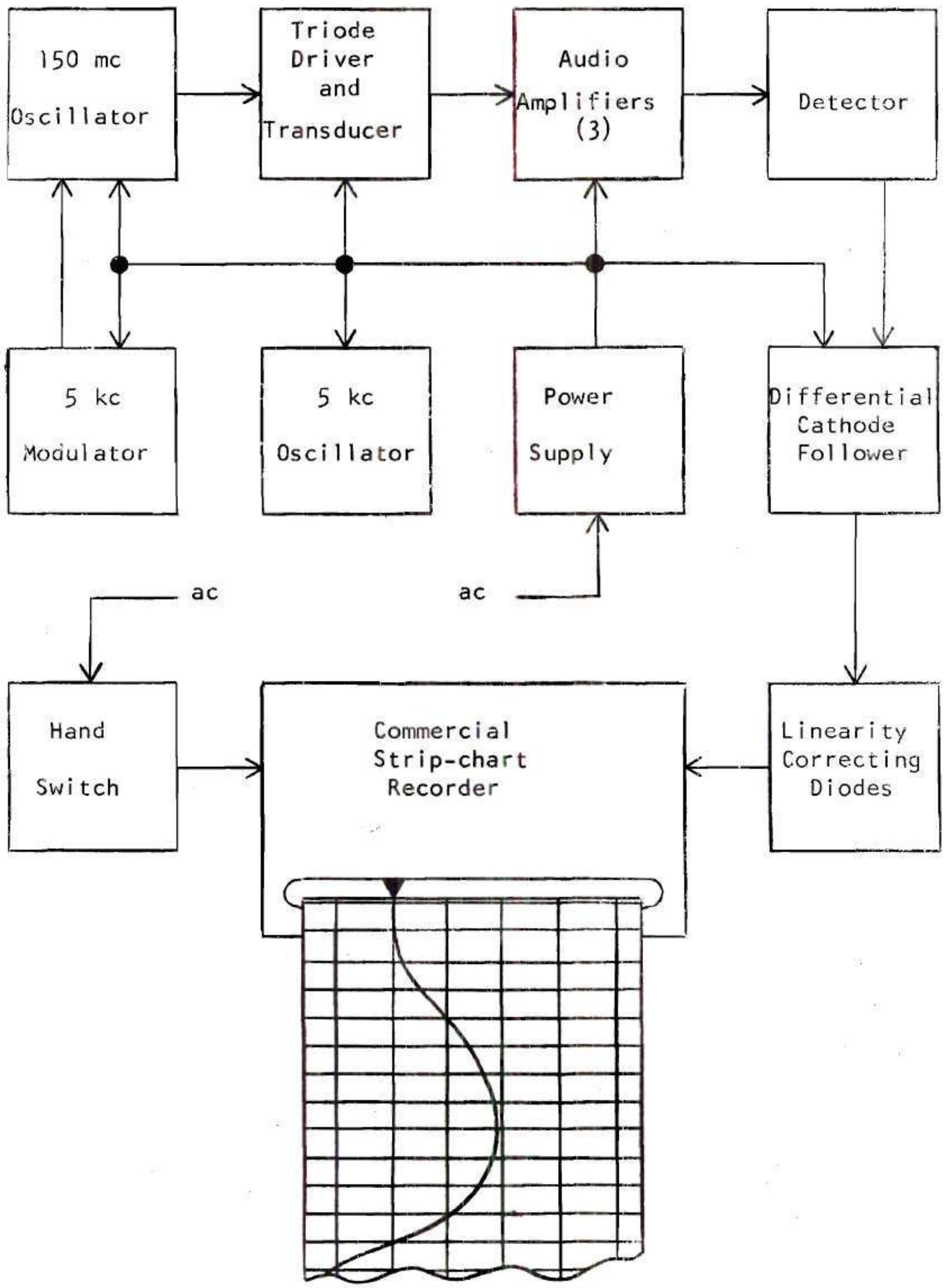


Figure 4. Block Diagram

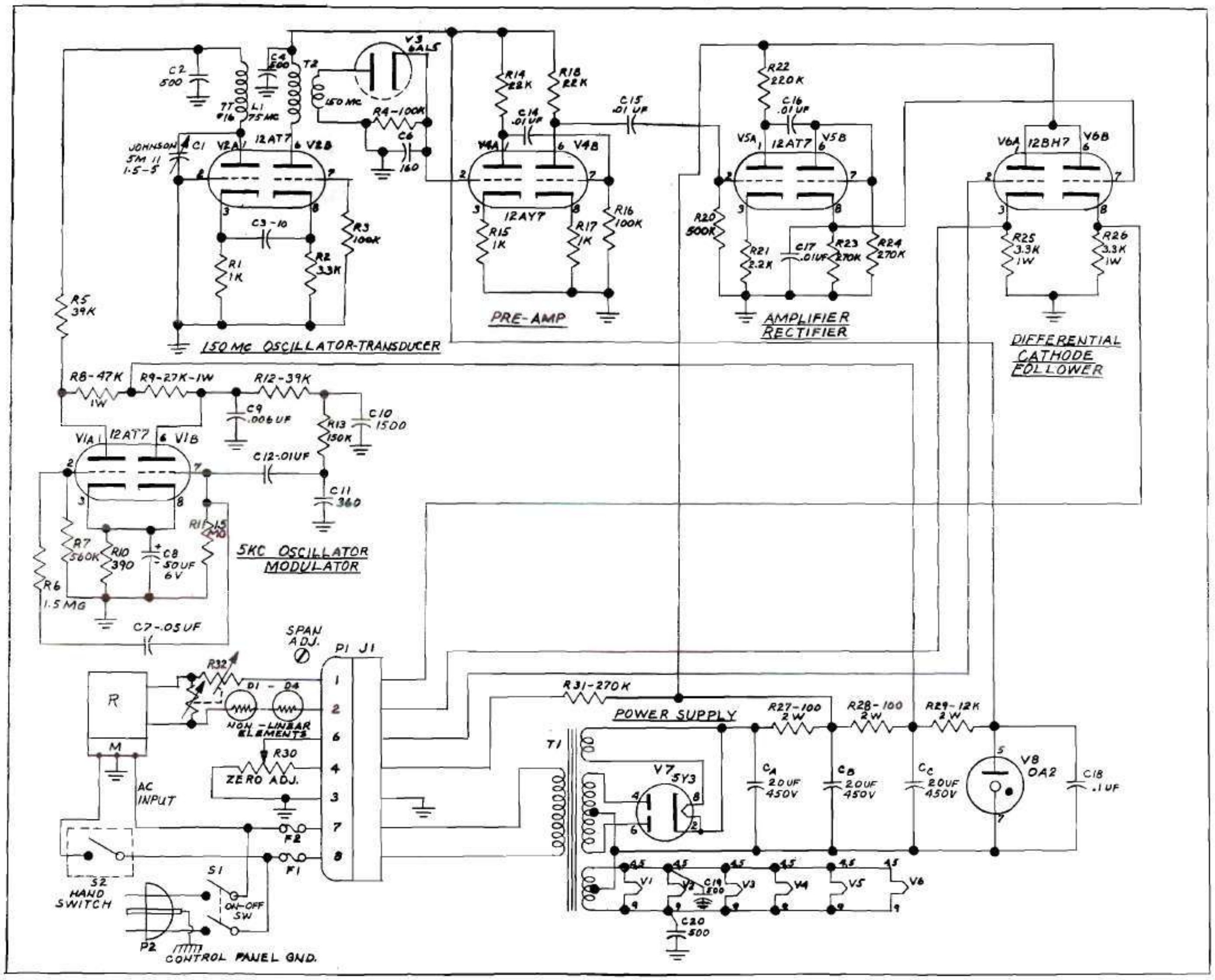


Figure 5. Schematic Diagram

strument and should be turned on at least one minute before using, earlier if the ambient temperature is below 70°F. Power Transformer T1 steps the 120 volts ac input up to 300 volts ac, and supplies filament power to all tubes in the instrument. The 300 volts ac is rectified by V7 and filtered to furnish plate voltage to the different amplifier stages. V8 is a gas-regulator tube which furnishes 150 vdc to V1 and the transducer section of V2B.

Mechanical Description

The mechanical layout of the instrument is shown clearly in Figures 6 through 12. With the exception of the flow-channel, none of the physical characteristics of the instrument are critical and were largely a matter of choice. It was desirable to have the instrument appear as natural as possible, so a standard commode seat was used as the starting point for the design. The instrument is a few inches higher than a standard commode, however, because of flow-channel limitations and a small raised platform is used for short patients. The instrument is used naturally by male (standing) and female (sitting).

The flow-channel consists of three parts: the stainless steel funnel, the curved copper pipe, and the straight polystyrene pipe. The funnel is constructed of sheet stainless steel and slopes downward from all corners of the commode frame. The various sections are soldered together and an oblong exit hole 1/2" x 3/4" is provided at the vertex and fitted with a standard, male, threaded, brass, 3/4" I.D., refrigeration-tubing fitting to accept the curved

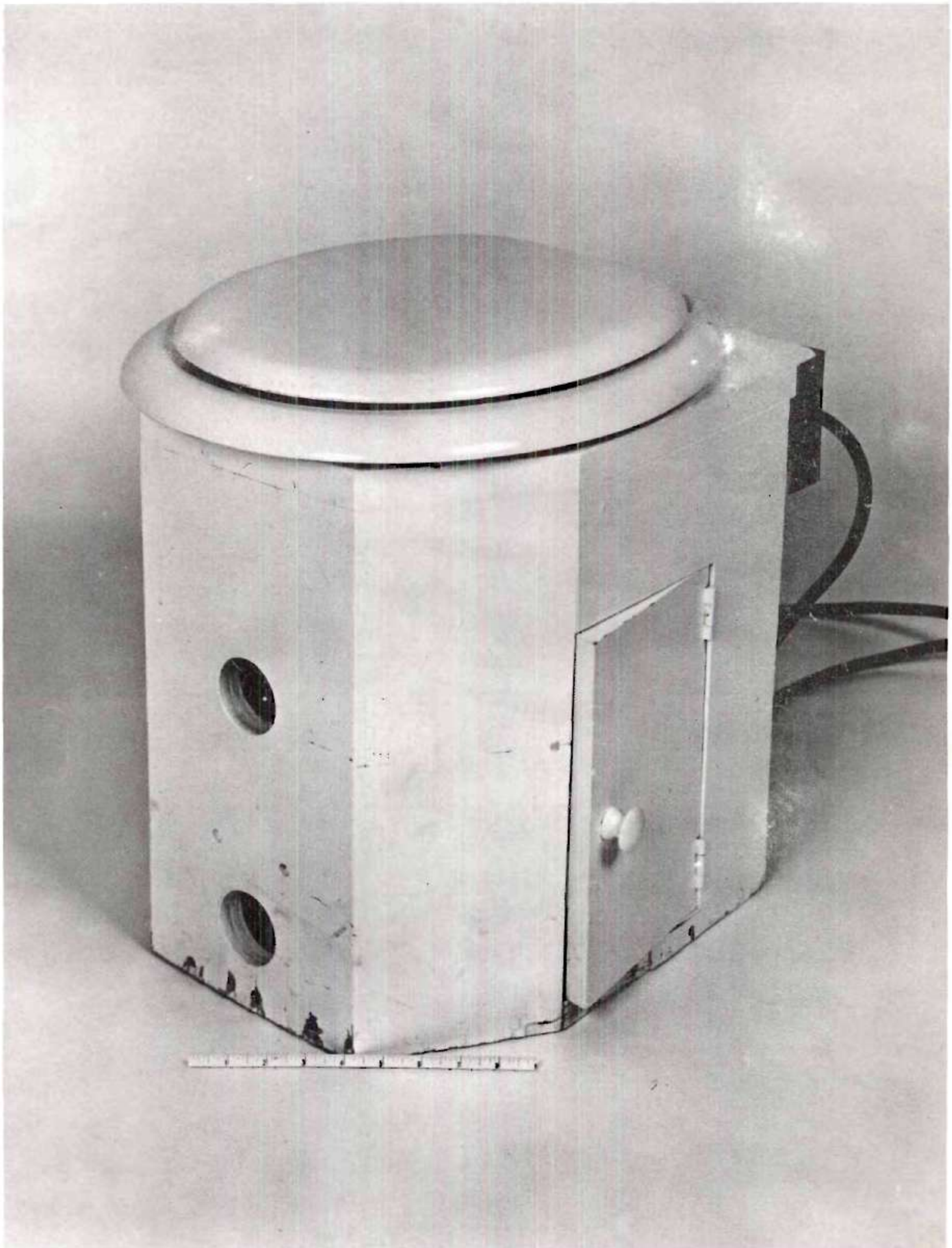


Figure 6. Front Perspective View, Commode

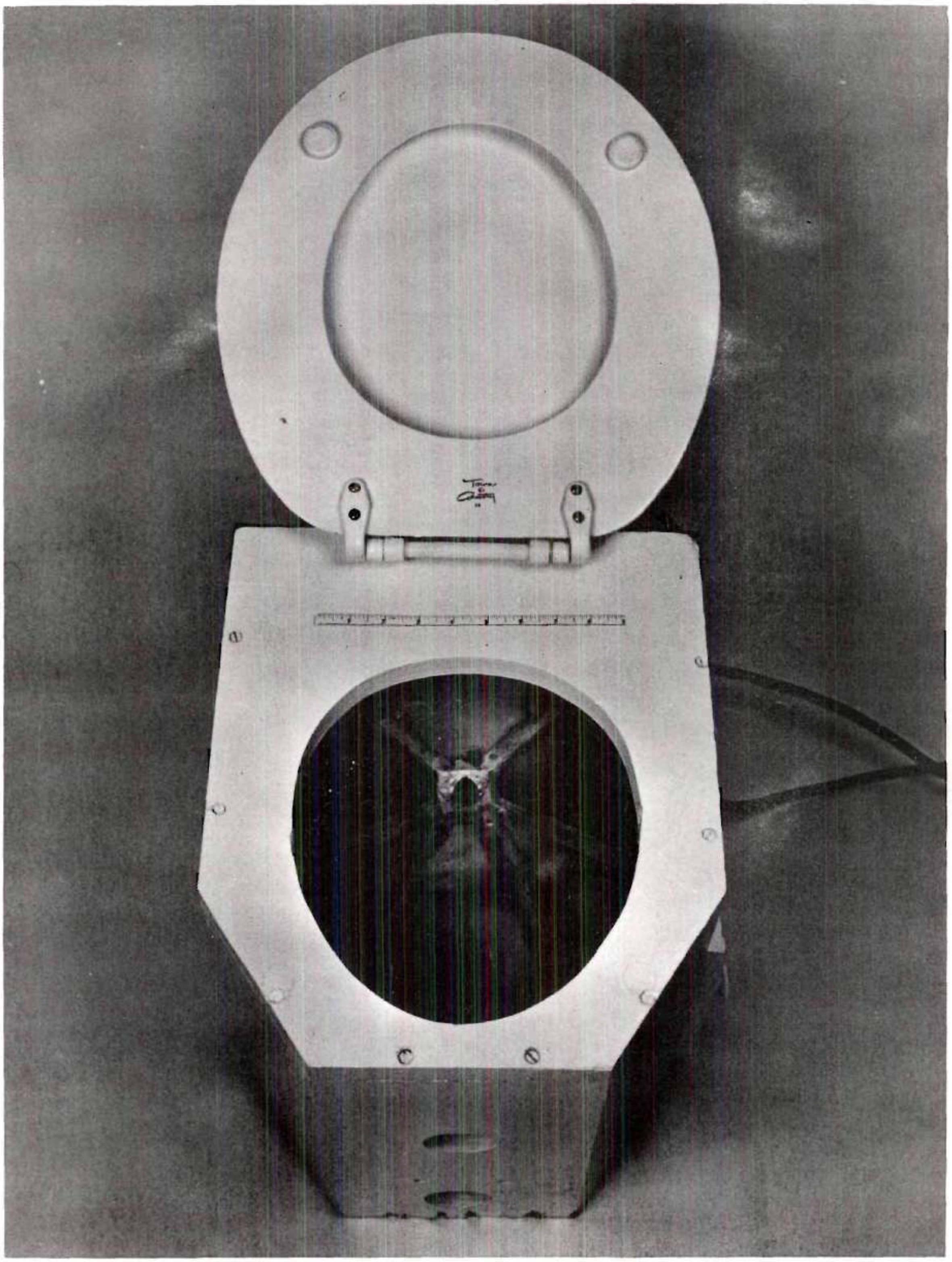


Figure 7. Top View, Commode

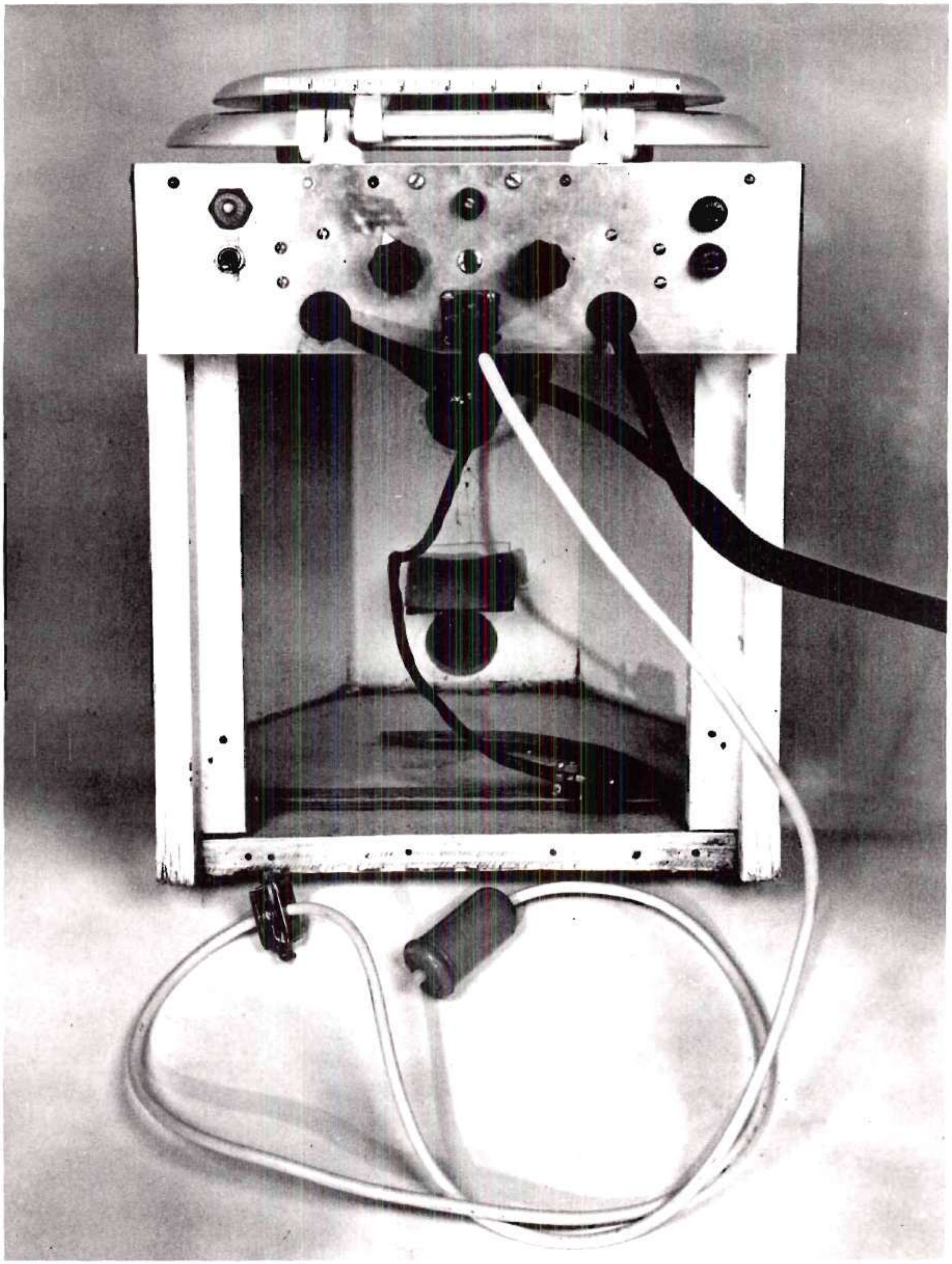


Figure 8. Rear View (Control Panel, Amplifier Removed), Commode

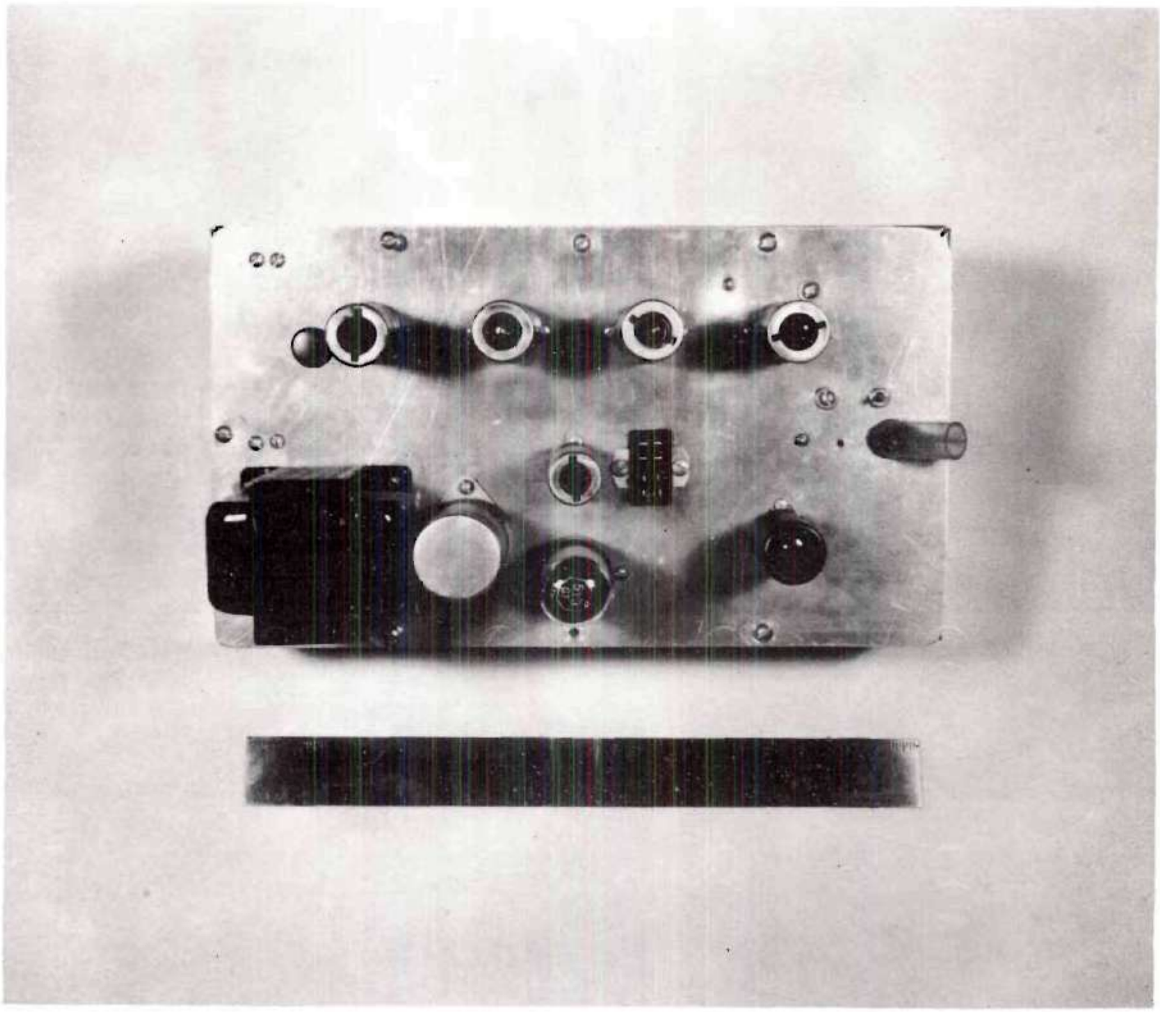


Figure 9. Top View of Chassis

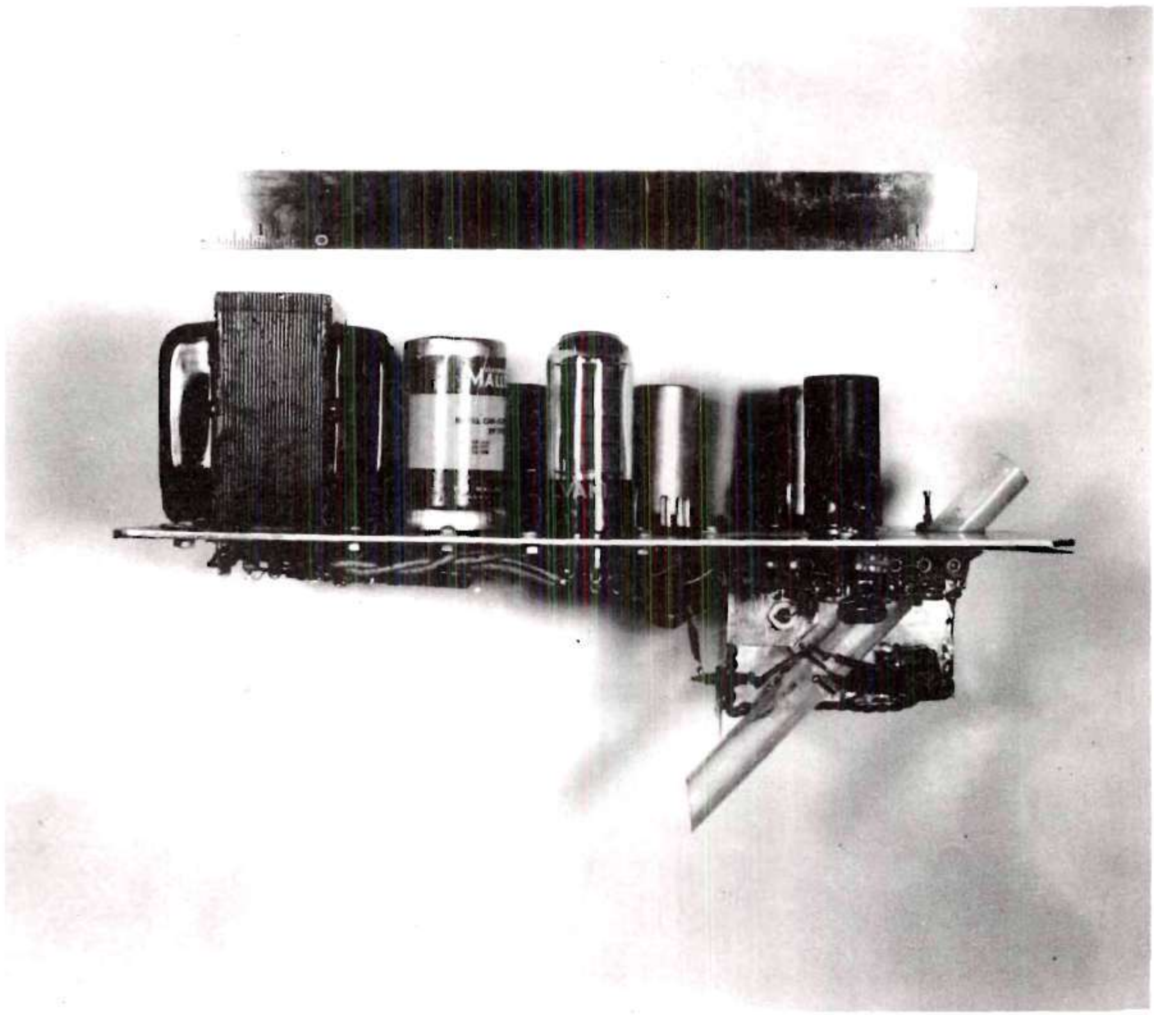


Figure 10. Side View of Chassis, Cover Removed

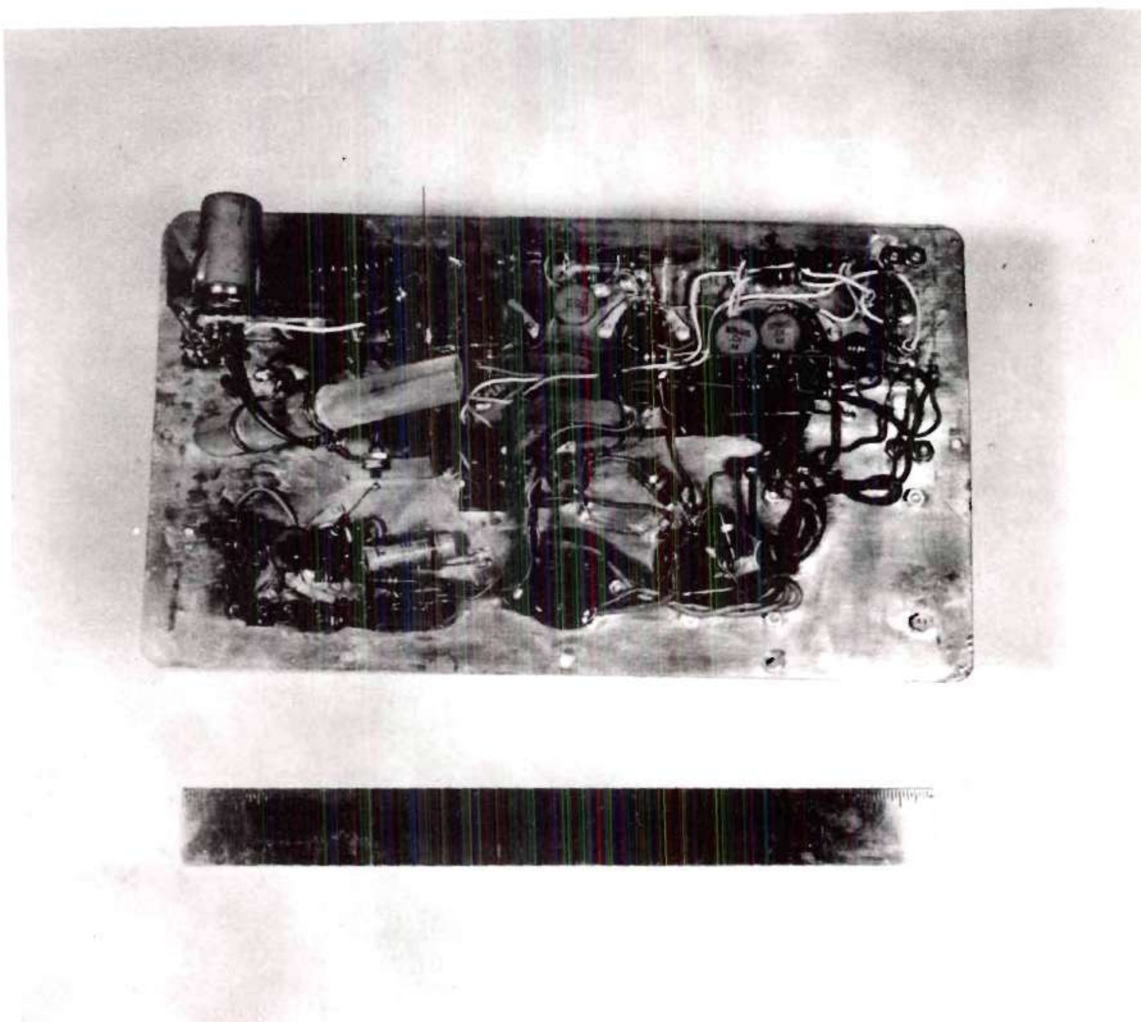
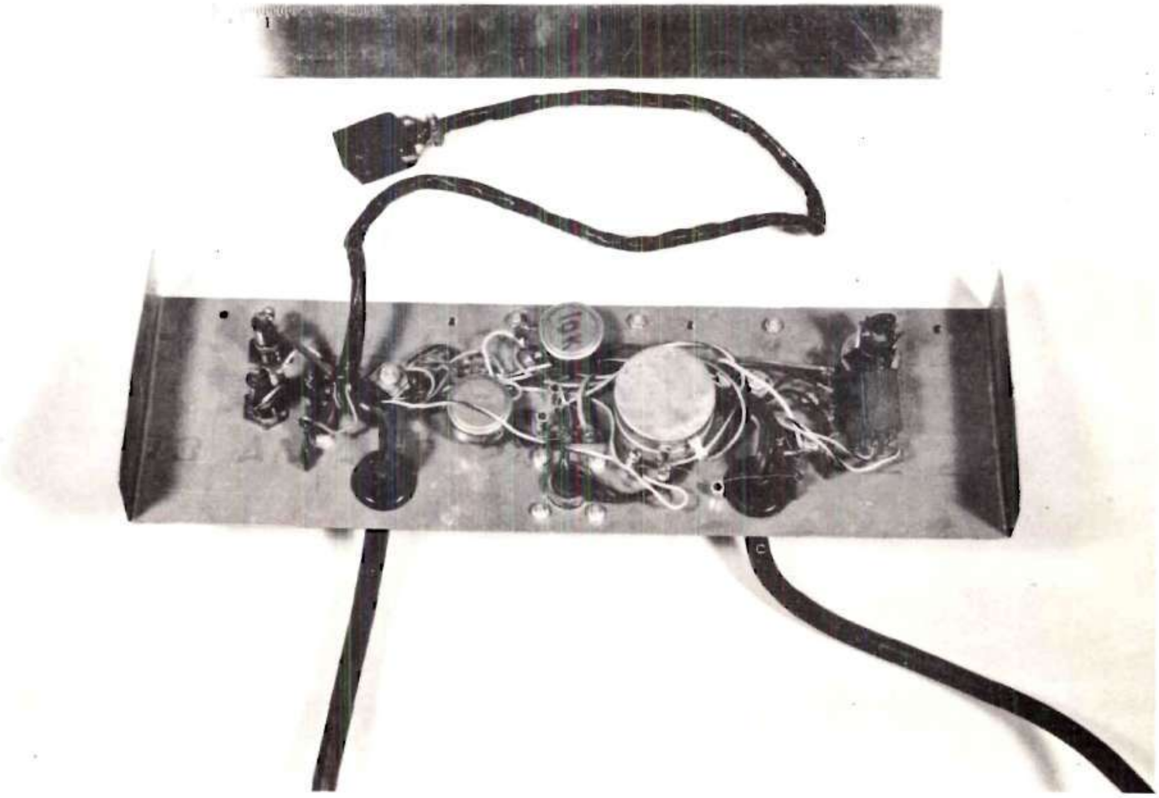
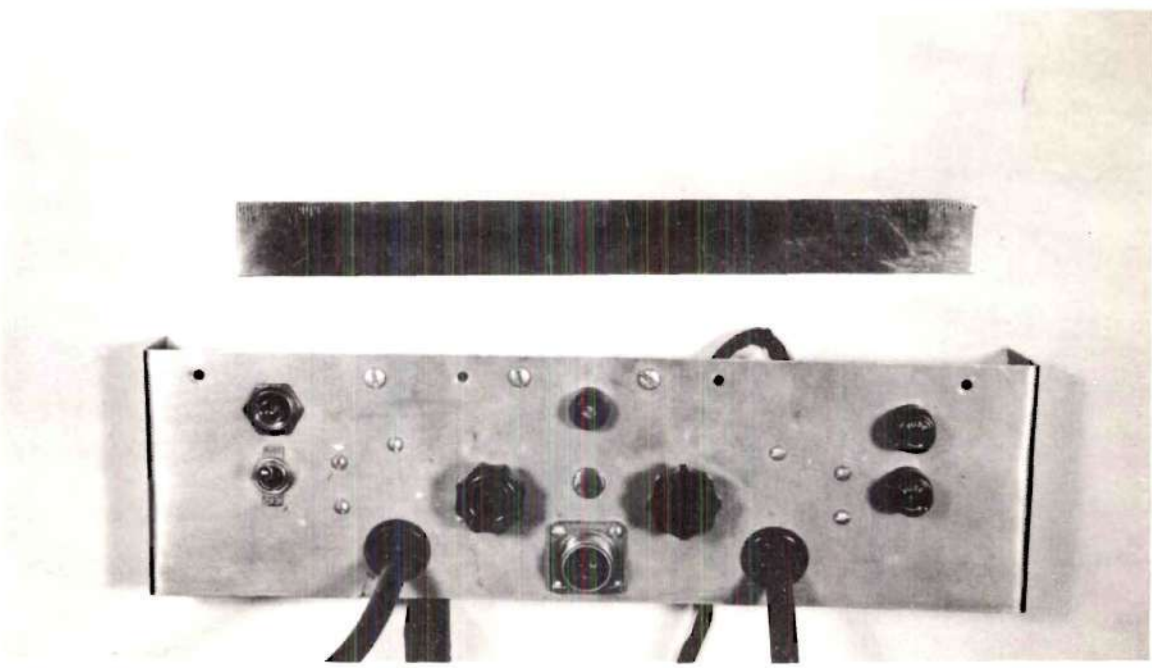


Figure 11. Bottom View of Chassis, Cover Removed



A. Rear View



B. Front View
Figure 12. Control Panel

section, which is fitted at one end with a female fitting.

The curved section, 3/4" I.D. except for output taper, is composed of a three inch straight section (which has the female fitting), a 1 3/4" radius "U" section, two 45 degree fittings and finally an output section taper, approximately 2 1/2" long, which tapers smoothly from 3/4" I.D. to 1/2" I.D. All pieces are soft-soldered together, and approximately three inches of the curved section at the junction of the 45 degree fitting and the output taper were filed away around the outside and inside turn and replaced with a flat side-plate (also soft-soldered) to form a nominally rectangular cross-section. This was necessary to prevent the liquid from flowing up on the side of the tube during the final turn and becoming turbulent. The curved section presents a unique appearance; however, it functions adequately to: 1. cancel out the initial velocity of the entering fluid and add a velocity due only to gravity without adversely affecting transient response or adding spurious fluctuations; 2. allow the positioning of the flow transducer directly under the funnel and thus make a compact unit; 3. allow the use of 1/2" I.D. polystyrene tube for the transducer section, which had been determined experimentally to be optimum for 0-50 ml/sec flow-rates -- the complete flow channel could not be 1/2" I.D. as this is too small to carry 50 ml/sec until the fluid accelerates under the influence of gravity. The fluid initially enters the curved section from the funnel at a downward slope toward the rear of about 10 degrees and maintains this slope until it enters the 45 degree angle sections, which combine to give the fluid a 45 degree downward direction, directed along the major axis of the instrument toward the front. A butt joint is formed at this point between the taper section and the straight pipe, a 1/2" I.D. polystyrene tube which serves as the transducer core and extends completely through the transducer chassis at a 45 degree angle to empty into the calibrated reservoir below.

The straight pipe section on the transducer chassis has a septum, approximately 0.01 x 0.1 inches, extending along the bottom the entire length.

This was found necessary to offset an unknown force (perhaps the Coriolis force) which, at flow-rates less than about 10 ml/sec, constrained the fluid flowing along the sloped straight section to follow an undulating spiral path and cause undesired fluctuations in the output signal.

Circuit Description

Basic Divisions

The basic divisions of the uroflowmeter are shown in the block diagram, Figure 4, and the schematic diagram, Figure 5. The basic divisions were formulated as shown prior to construction to preclude the use of rf amplifiers and dc amplifiers, if possible, since considerable care must be used in the construction of these usually critical stages. Standard circuits were selected for the 5 kc oscillator [22], and audio pre-amplifier and amplifiers [23]. The detectors and differential cathode follower are also of rather ordinary design. The final design included all divisions of the conceptual design except for the addition of the non-linear 1N2326 diodes D1, D2, D3 and D4 which were found to be necessary to attain the desired linearity of the output with flow. The output circuitry was initially designed for direct drive of a one millampere recording ammeter of nominally 1500 Ω resistance. At the time of the design freeze and start of construction, it was felt this design would furnish capability for use with any recorder selected. The hand switch is a standard hospital-type switch which is very convenient to use. The patient (or operator) has to push the switch contact down to start the chart paper and push the rim of the switch to stop the paper.

The power supply is of conventional design, using a power transformer to supply the high voltage necessary for operation. The gas regulator tube was included to ensure stable operation of the oscillator circuits. The power transformer also allows isolation of the chassis from the ac input power line, an added safety advantage.

Oscillators

The conceptual design called for two oscillator circuits: a 150 mc oscillator and a 5 kc oscillator whose output modulates the 150 mc signal to circumvent the need for dc amplifier stages. The oscillators were not felt to be critical since nothing in the device makes use of any precise frequencies and the output is essentially direct current to the recorder.

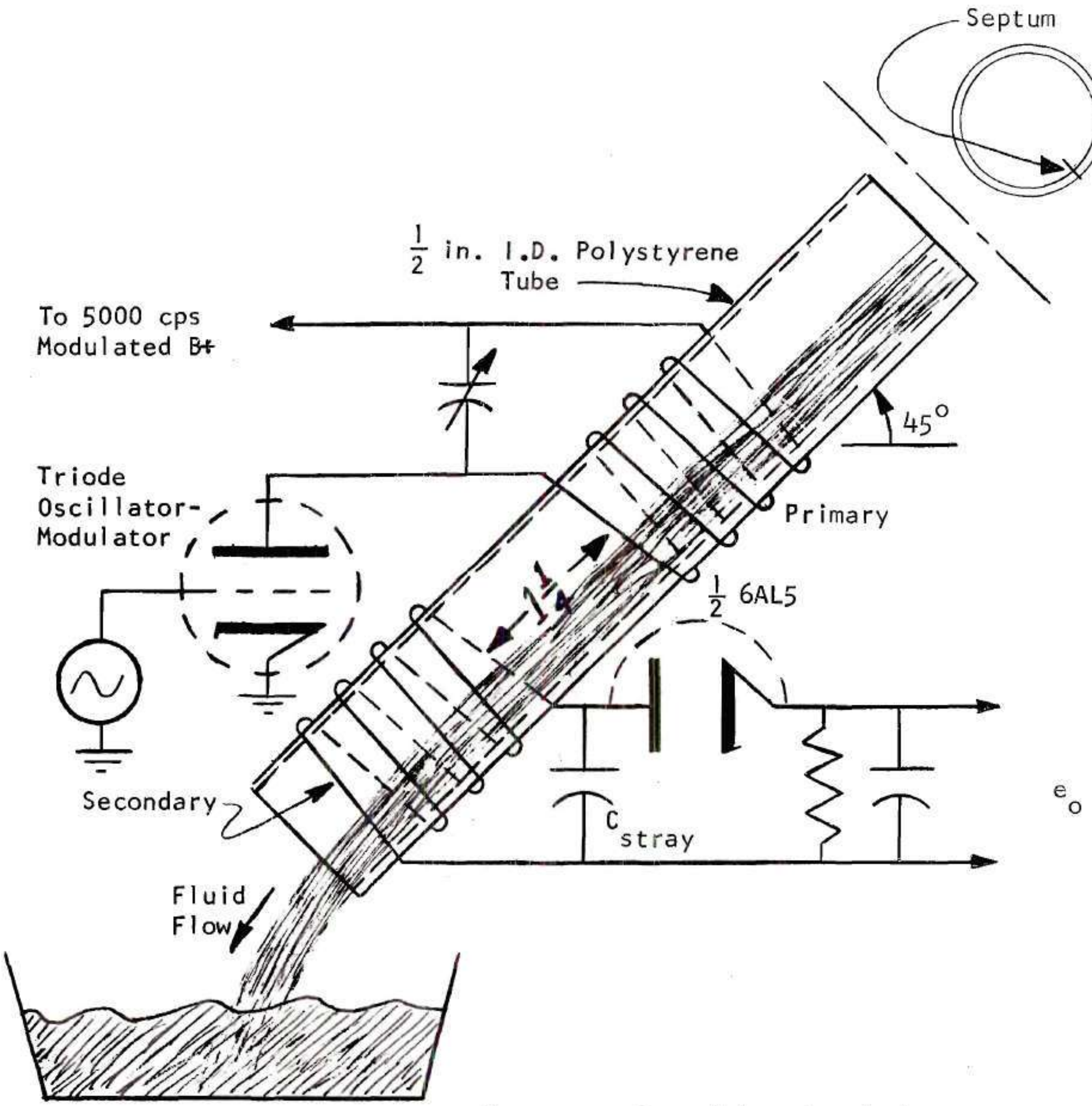
The 150 mc oscillator-modulator (V2) proved to be the most troublesome of the two, it being desirable to combine the 150 mc oscillator with a modulator for amplitude modulation of the audio signal onto the carrier. The 75 mc oscillator section (V2A) is a tuned plate oscillator with cathode coupling to V2B, which operates as a frequency doubler. The transformer primary (T2) is tuned to 150 mc with a relatively low Q causing the circuit to be relatively free of critical requirements for frequency stability. The frequency has been varied one megacycle either side of the nominal center frequency with no particular changes in calibration or operation. Some problems were encountered with 60 cps hum, but since the final recorder is insensitive to this "high" frequency no particular efforts were made to remove it completely and there is no evidence of it in the uroflowgram. The oscillator-modulator (and transducer) were constructed using conventional techniques for this frequency. Tin-plated steel, reinforced with aluminum backing, was found to be very convenient during construction. The construction shows visable evidence of minor changes, but this is considered inevitable in a prototype model..

The 5 kc oscillator is a conventional RC phase-shift oscillator. A cathode-follower is used to couple the 5 kc signal to the plate of 75 mc oscillator V2A, resulting in approximately 75 per cent amplitude modulation for the parameters chosen. One hundred per cent modulation gave a larger output value but there is no final difference between varying modulation index and varying the gain of the audio amplifier stages, and adequate signal is available at the output stages using a 75 per cent modulation index.

The Transducer

After many false starts, a new transducer for low open-channel flow rates has been designed, constructed and tested. The configuration is as shown in Figure 13. Fluid in the tube, which is the transformer core, varies the transformer parameters to cause the output voltage e_o to vary with flow. Several attempts were made to correlate dielectric constant and loss tangent of the fluid with transformer parameters, but it became obvious that this would make a thesis in itself since no reference was found in the literature on the effects of liquids on transformer parameters and everything noted about the transducer was non-linear. For instance, varying the salt content (loss tangent) of the fluid will cause e_o to vary as much as 300 per cent or as little as ten per cent (for a given flow) depending upon coupling between primary and secondary and primary tuning. Also, if a smaller (1/4 inch I.D.) tube is filled with a lossy fluid, sealed, and used as a probe in the larger tube, e_o varies as much as 75 per cent depending on the location of the smaller tube in the transformer core.

For reasonable dynamic range and linearity, it was empirically determined that a low circuit Q would be required. By varying the tuning of the primary significantly, e_o can be made to vary either up, down or not at all with flow. The secondary, being essentially untuned and loosely coupled, was found to be little affected by flow rates. Again it was determined empirically that



Note: e_o is a 5 kc signal whose amplitude is a function of the instantaneous volume of liquid in the tube. For a given velocity, this is proportional to flow rate.

Figure 13. Transducer Configuration

best overall results were obtained with an untuned secondary and that loading the secondary only attenuated output voltage without appreciably affecting the shape of output versus flow characteristics.

One investigator [24] had this to report on a 400 mc investigation:

> The author has long been curious about the effects of liquids on circuit Q. This curiosity led to ... (an) experiment, performed to determine the effect of tap water on circuit Q with and without a few salt crystals added. Q2 measured for the clear water was 610 (Q1, before adding to the core, was 630). Low losses, very little change in inductance, and approximately one per cent change in distributed capacitance were noted. A pinch of salt (NaCl) was then added and the effects noted. Q2 dropped to 255, with no change in inductance apparent. It can only be concluded then, that the RF resistivity or losses only change in a positive direction with the addition of salt.

The observations by this writer were consistent with the above comments, although the transducer used in this thesis is never full of liquid and the frequency is lower (150 mc). It is worth noting that this [24] is the only reference found on the affect of liquid on coil parameters; none at all were found on transformers as such.

Figure 13 is an accurate representation of the transducer windings. No. 14 A.W.G. transformer wire was used and wrapped tightly around the polystyrene tubing. Polystyrene cement (Q dope) was used to prevent relative movement of the tubing and windings. The secondary was slid up and down the tube until an appropriate location was noted which gave desirable characteristics -- then the coil was cemented into place. It is quite likely that an entirely different circuit arrangement will give desirable results.

For instance, 150 mc could be obtained from a high impedance source and the primary loaded with a variable resistance to obtain the desirable low Q circuit, depending upon dynamic range desired. One thing apparent from the investigation was that the larger dynamic range needed, the lower Q required. Sensitivity of output voltage to flow increases significantly with a higher Q, but dynamic range decreases.

As previously mentioned, the transducer operates independently of flow in the normal sense. It is only the mechanical arrangement which allows sensing of flow with this type of element, and for a given amount of liquid in the tube the output is the same whether or not there is actually flow of the liquid. Considering the presence of the fluid in the tube and the fact that the secondary is loosely coupled to the primary, an appropriate equivalent circuit for the transducer would appear to be that of Figure 14. It can be shown that the resonant frequency f_o is given by:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \sqrt{\frac{L - CR^2}{L - CP^2}}$$

This expression indicates that changes in R and P, which occur of course when a lossy liquid is introduced into the core, cause changes in f_o. The use of the triode driver essentially introduces a large R and decreases the effect of changes in R when the loss tangent i.e., salt content, changes. This, in effect, causes circuit changes to be more a function of C than on R, and Quinn [24] has shown that C varies when liquid is introduced into

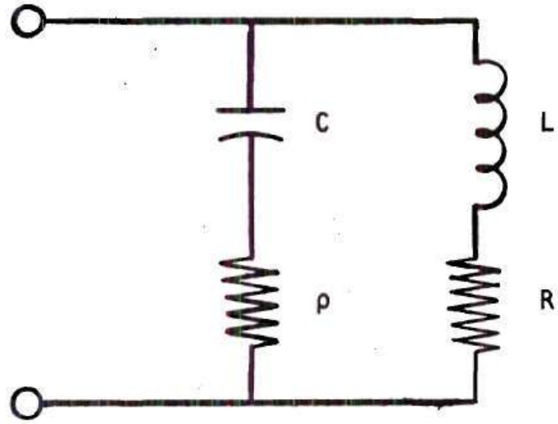


Figure 14
Transducer Equivalent Circuit

the tube.

It was found during the construction of the transducer that by varying L (adjusting coil winding spacing) and C (using a trimmer in conjunction with tube plate capacitance and distributed capacitance in the coil), almost any desired curve of output (see Figure 15) versus flow could be realized. One arrangement gave almost perfect linearity but the output was found to change significantly with salt content of the fluid and a compromise was made which called for introduction of non-linear diodes in the output to obtain linear relationships. It is quite probable that other circuit arrangements utilizing similar variations in circuit parameters would yield a suitable, and equivalent, flow transducer or device for other sensing applications as described in Chapter V.

The first detector, V3, is mentioned under this heading since it forms an integral part of the transducer if one considers the five kilocycle per second signal to be the output of the transducer. The circuit is a conventional half-wave rectifier with RC filter. The filter parameters have no appreciable affect on circuit operation, and a tube was used rather than a solid-state diode simply because of temperature considerations encountered during testing. At one time, a IN295 diode was installed but thermal coupling to the liquid flowing through the tube caused the output to vary somewhat with the temperature of the liquid. The 6AL5 gives essentially the same results as a IN295 diode without the adverse temperature effects. Once this circuit has warmed up for a few minutes, no appreciable temperature affect can be noted for

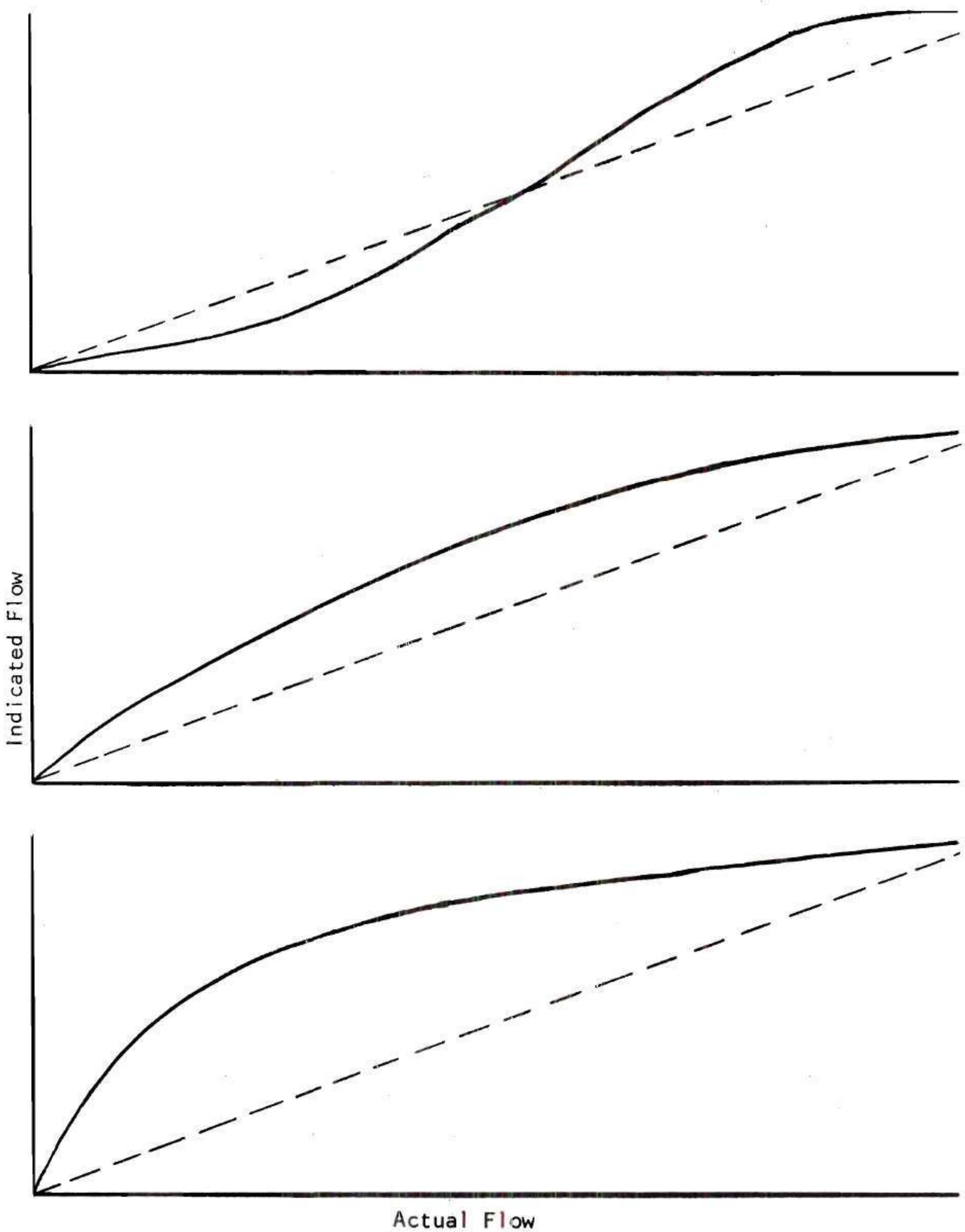


Figure 15

Typical Curves of Indicated Versus Actual Flow (Tap Water) Without Non-linear Correction Circuit.

liquids flowing in the tube and the presence of the diode within the enclosed chassis was found to considerably stabilize circuit operation with changes in ambient temperature.

Amplifiers and 2nd Detector

The audio amplifiers are constructed using a handbook [23] construction reference. No appreciable changes in gain have been noted, and since the signal amplitude variations are well within the linear operating ranges of the circuits, no changes in gain are expected that cannot be easily compensated by adjusting R30, Zero Set Control. The second detector is a diode-connected triode and was used because it was there: two dual triodes were initially installed but it was subsequently found that three audio amplification stages were sufficient and the triode section was surplus and could be used as a detector. The graphical transfer function of the complete circuit from the diode load resistor R16 to the output current flowing through the recorder is shown in Figure 16, taken with both oscillators removed and the non-linear diodes D1 - D4 shorted. The signal generator was connected directly across R16; variation of signal generator frequency indicated the 3 db points of this portion of the circuit to be 480 cps and 67 kc. The quiescent voltage across R16 is balanced out by Zero Set Control R30 during normal operation.

Output Stage and Adjustment

The output stage is a conventional differential cathode follower-driver with Zero Set and Span Controls and supplies sufficient current to drive a one milliampere recording ammeter (strip-

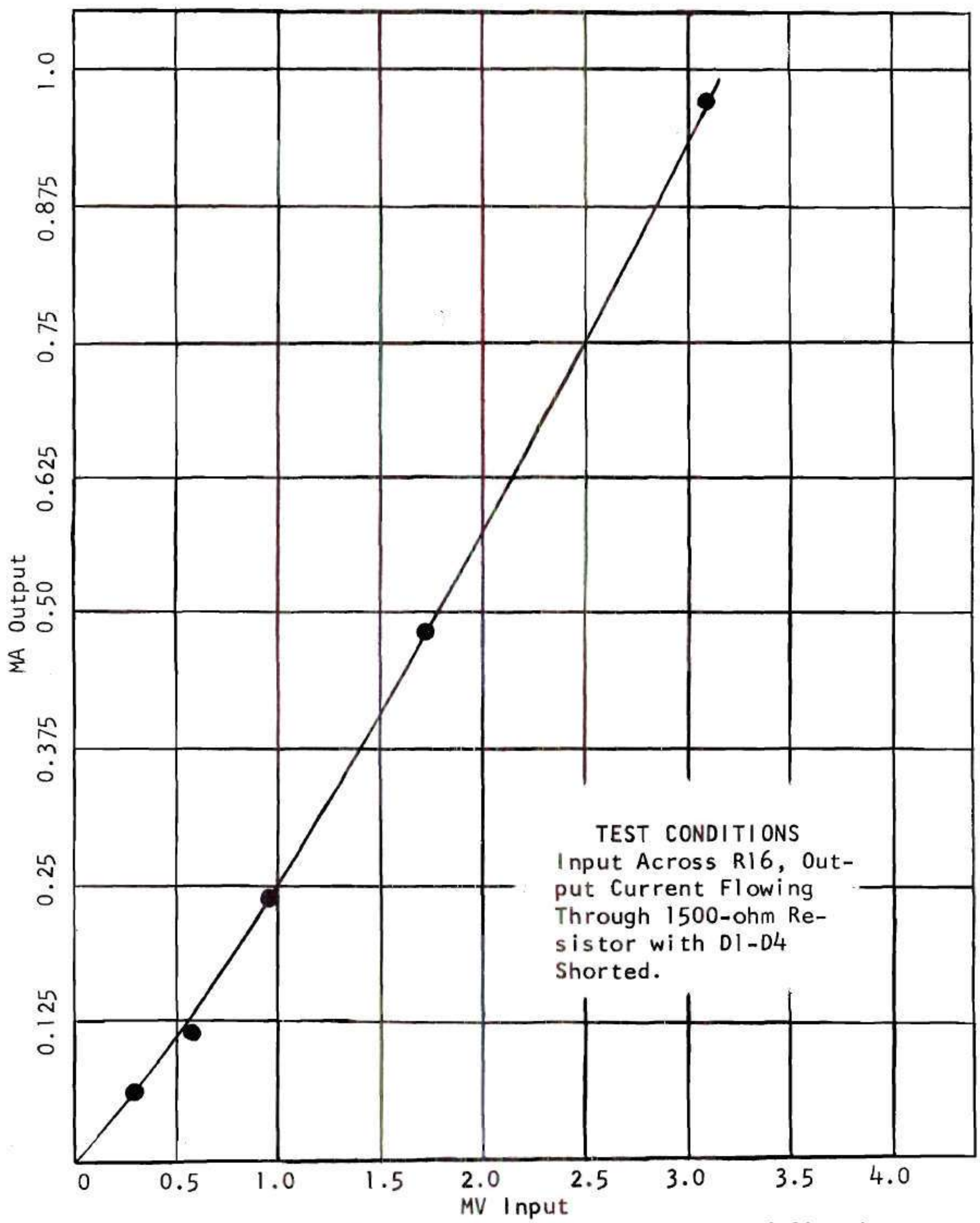


Figure 16. Graphical Transfer Function of Portion of Circuitry

chart recorder). One section of the differential cathode follower has a Zero Set Control, R30 which is an operating adjustment available on the Control Panel at the rear of the instrument. After the instrument has warmed up for a minute or two, if the recorder pen is not indicating zero, R30 is adjusted until this condition is met. This control balances out the signal which is coupled quiescently through the transducer transformer, and has been found to be quite stable, requiring only occasional adjustment.

The only other operating adjustment is the Span Control, R32. This control is a radio L pad and is adjusted to cause the standard flow device supplied with the instrument to read 25 ml/sec when using 0.5 molal solution of salt (NaCl). Relatively infrequent adjustment is required of this control also, but different calibration factors can be derived as this is a linear adjustment and the scale factor can be changed to allow very small flow to give a large reading. When adjusted as described above for the standard flow device, a nominal 0-50 ml/sec linear dynamic range is available although a correction factor may be necessary for some urine samples. Calibration and derivation of correction factors is described in the next section.

Since adequate linearity could not be obtained directly, the addition of non-linear diodes was required to effect desired recorder indications with input urine flow. The final stages characteristics with the IN2326 non-linear diodes are shown in Figure 17. Figure 18 shows the characteristic of a IN2326 diode. Use of

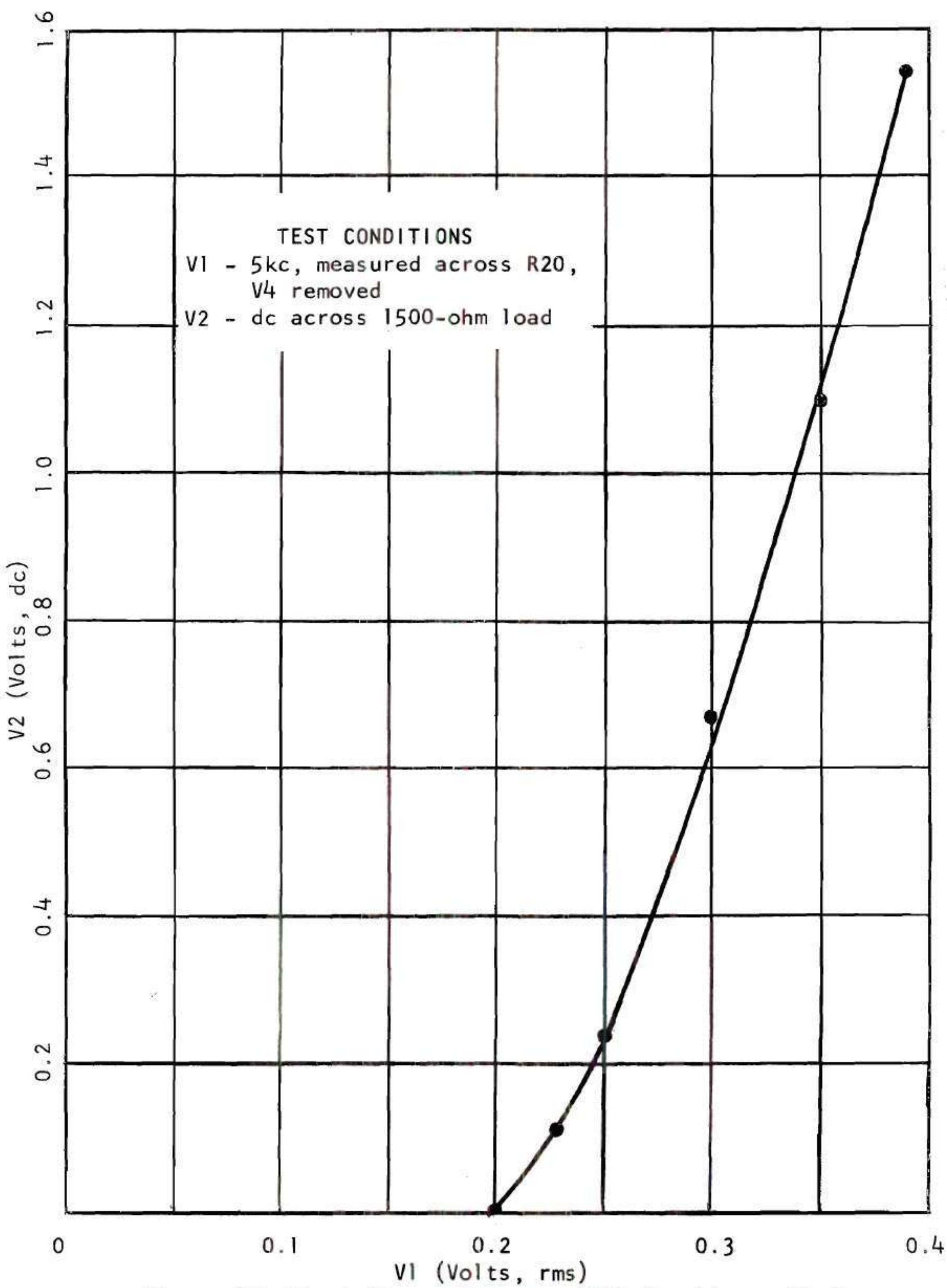


Figure 17. Final Stages Response With Non-linear Diodes

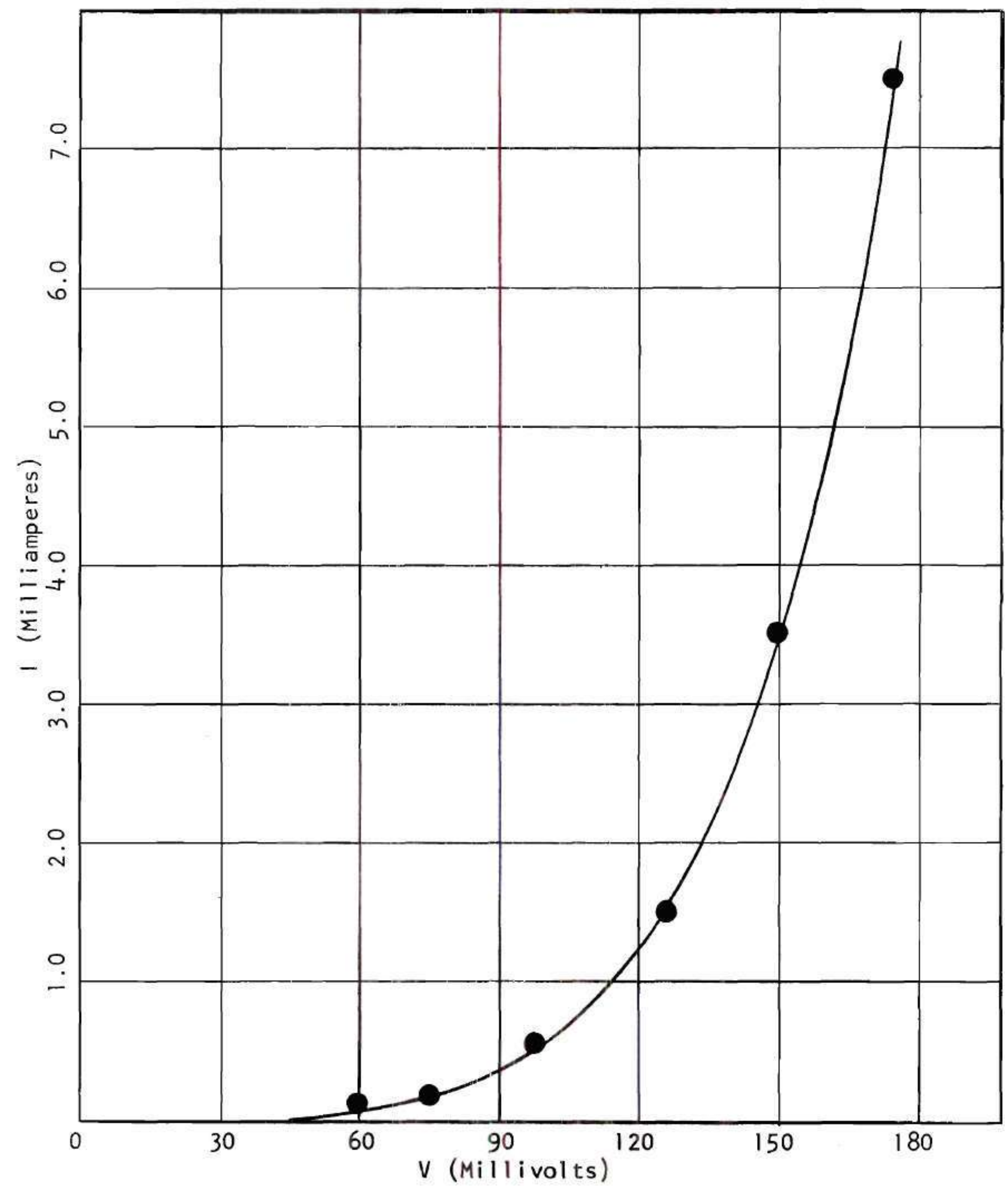


Figure 18. IN2326 Characteristics

these diodes led to the requirement for an audio L pad as the Span Control since it is necessary to keep essentially the same circuit impedance for different span adjustments to maintain linearity.

Calibration and Correction

One of the secondary goals of the original undertaking was not met: operation independent of urine composition. It became apparent during the preliminary testing of the instrument that urine composition variations may lead to intolerable errors. Since it was easily correctable when in error, and scrapping of most of the effort to date would be required if this correction was not allowable, the preliminary conceptual design was adhered to since it would obviously lead to an otherwise desirable instrument. Calibration and correction of the instrument is simple and straightforward: the writer's ten year old daughter has computed correction factors after only 10-15 minutes of instructions; only the initial calibration has been required to date.

Calibration is accomplished by use of two standard flow devices supplied with the instrument. The two devices provide flow rates of 15 ml/sec and 40 ml/sec respectively when filled with 0.5 molal saline solution. Span Control R32 should be adjusted until proper readings are obtained for each flow device, with slight readjustment of the Zero Set Control R30 required. Calibration will be required only in the event of failure of the non-linear diodes D1 - D4 or gross changes in associated resistors but should be checked every few months.

Correction of the urine flow reading after each use is required, and the correction factor should be noted on each uroflowgram. The correction factor, either greater or less than unity is obtained by taking a 50 milliliter sample of the urine into a standard flow device furnished with the instrument which should give a reading of 25 ml/sec when allowed to flow through the uroflowmeter. If the sample gives a reading, say X, which is less than 25 ml/sec then the scale factor which is applied to that particular uroflowgram is 25/X; conversely, if the 50 milliliter sample gives a reading greater than 25 ml/sec when allowed to flow through the standard flow device and the uroflowmeter, then the correction factor is X/25, X again being the observed reading. Similar correction factors are easily derived if one wishes to change the scale of the instrument, perhaps for an extended study of urine flow of children.

Construction of an instrument which would not require computation of a correction factor is feasible and a conceptual approach to the instrument is given in Chapter V.

CHAPTER IV

TEST AND EVALUATION

Objective

A measuring instrument is of little value unless the characteristics of the instrument under existing operating conditions are known. For this reason, it was decided that the major objective in testing and evaluating the accuracy of the instrument would be to furnish data the user would seek in answer to questions which may arise during operation. Since accuracy and reliability cannot be tested into an instrument, these factors were considered during development; the purpose of testing the instrument was to evaluate these characteristics.

The normal use of the instrument will be in the urologist's office or perhaps in a hospital or mobile medical trailer; the period of operation can range from a few minutes to perhaps all day, but will normally be in an air conditioned environment. Thus, environmental factors were minimal.

The parameters considered of importance in evaluation of the instrument were linearity, rise time, fall time*, sensitivity to urine (salt) composition, linear dynamic range, zero and calibration drift, repeatability, and absolute accuracy.

*Ordinarily rise time and fall time for a rectangular pulse in electronic circuits are directly related, but the non-linear action of the mechanical channel required measurement of both fall time and rise time.

Test Description

To evaluate the parameters listed in the previous section, two types of tests were run: steady state and transient. The steady state tests were made using a capacious container whose output was relatively constant for 5-10 seconds, allowing steady state conditions. The flow of the large container for a particular volume, or head, had been previously calibrated using a stop-watch and calibrated beaker. The change in flow rate was less than one milliliter per second for the period of interest.

To generate a step input of constant flow rate for evaluation of transient performance, the flow from the large container was interrupted by placing a finger over the hole emitting the stream and removing the finger quickly.

Instrumentation

The instrumentation used for the testing and evaluation consisted of the following items:

Sensitive Research DC Voltmeter

Sanborn Recorder

2500 ml Container

500 ml Container

500 ml Calibrated Beaker

Stop-watch

Various Saline Solutions

Urine Samples (several)

The Sanborn Recorder was used for measurements rather than the Esterline-Angus Recorder for two reasons: the Sanborn Recorder indicates--with its superior frequency response--more closely the true transient response capability of the instrument, and the accuracy is much better than the Esterline-Angus Recorder. Since the instrument will operate with almost any recorder, the recorder actually used is optional and it was not desirable to furnish the rise time of the recorder as indicative of the total capability. The rise time of the uroflowmeter is much faster than that of the Esterline-Angus Recorder. Also, the Sanborn records are more suitable for reproduction.

Results

The transfer function for the output circuitry is shown in Figure 17. A 1500-ohm (dummy recorder) load was used for this test, since the transfer function is dependent on the value of the load resistance.

The transfer function shown in Figure 17, when coupled with the non-linear output of the transducer T2, combine to give the recorder indication (current) versus flow shown in Figure 2. A dynamic range of zero to fifty ml/sec is apparent. Exceeding 50 ml/sec causes no damage to the instrument.

The transient response, indicating rise time and fall time, is shown in Figure 3. The rise time is excellent for the purposes intended, although the output is delayed by the time it takes the flow to reach the transducer transformer. The fall time is critically dependent on the shape of the flow path, and could probably be improved at least an order of magnitude by an optimized flow channel. The fall time is, however, considered marginally adequate for the intended purpose.

Zero drift of the instrument, after reaching operating temperature, was found to be negligible. The Zero Adjust Control usually has to be readjusted prior to each test during the first few minutes of operation.

While diligent efforts were made to develop a uroflowmeter insensitive to salts in the urine (or fluid), this aim was not met. A calculation of a correction factor must be made after tests with each fluid. This calculation, described in detail in the last section of Chapter III, is easily derived and leads to the correct value for flow with a possible error or five per cent of full scale. Recommendations for an instrument free of this inconvenience are given in Chapter V.

The repeatability of readings taken with the instrument has been found to be one to two ml/sec; this spread encompasses tests made with many different molal solutions and urine samples.

The absolute accuracy of the instrument, after correction constant is applied, is about five per cent of full scale value.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Sources of Error

Principal sources of measurement error of the instrument described in this thesis are involved in the mechanical/electrical interface which occurs in the transducer transformer, and sensitivity to salinity. It is felt that the design of an optimum flow channel would lead to an instrument with excellent linearity and fall time under transient conditions. The flow channel around which the transformer could be built would not, however, be a right circular cylinder as was used in the instrument described in this thesis. If the cross section of the cylinder were shaped empirically to cause the output of the transducer to be linear with flow, construction of a next generation uroflowmeter would be greatly simplified since the output stages would be linear. There is strong evidence that an optimum cross section flow channel exists: the position of the fluid in the core has been found to change the output significantly. Increasing the tilt angle and optimizing the length of tubing used to remove initial velocity given urine by the patient could probably increase the fall time by an order of magnitude or more.

Possible Improvements

A number of improvements have become apparent since the design and construction of the present instrument was completed. Improvement of the flow channel along the lines mentioned in the last section should be extremely fruitful, but should probably be attacked by someone well versed in the technology of open channel flow.

Linearity

While the linearity of the instrument as devised appears adequate, it would be desirable to achieve linearity without the use of the germanium diodes. In the present configuration the value of the load resistance changes the linearity of the output with flow. While this poses no particular problem with the instrument described here since a 1500-ohm recorder (or dummy load for testing with the high input-impedance Sanborn Recorder) is used for this instrument, the utility of instruments of this type would be enhanced by being adaptable to any recorder, with no severe restriction on the input impedance of the recorder.

If the design of a new flow channel did not achieve linearity, then the output stages should be designed such that changes in load impedance have no affect on calibration. This could be attained with the use of an additional cathode follower stage between the germanium diodes and the load.

Urine Composition Sensitivity

The changes in indicated flow with the composition of the fluid is a major inconvenience. While easily correctible after the patient has left, a change in the uroflowmeter is desirable to eliminate the calculation of correction factors.

The most obvious way to eliminate the sensitivity to urine composition is to build two transducer transformers in the form of a bridge circuit, with one element sensing both flow and urine composition (as now) and the second element consisting of a tube which fills up and then has an output dependent only upon the urine composition. This could be easily accomplished by converting the present flow channel into a λ shaped channel, with the single tube represented by the longer arm leading to a device similar to the present one. The vertical arm would be almost stopped up such that it would readily fill with about five to ten milliliters of the fluid under test. Around this vertical arm (which is full of fluid during the test), the second transducer transformer could be constructed to give an output proportional to urine salt content. This dc voltage could be used to bias a variable μ tube to chain the gain of the output stage.

With the gain of the output stage proportional to urine salt content, this factor would be effectively removed automatically. More effective means may be found for automatic correction, but the foregoing approach is certainly feasible.

Volume Totalizer

The addition of a volume totalizer would allow the urologist to study flow versus accumulated volume, as there is some evidence that this chart may be of some value.

A volume totalizer could consist of either an electronic integrating circuit to integrate the output voltage which is proportional to flow, or could be accomplished by electronically weighing the collecting pan. The latter method has been used in some uroflowmeters and is easily implemented. An X-Y recorder would be required for plotting output data.

Dynamic Range Extension

The present upper limit of the dynamic range could be extended several orders of magnitude since a device would be constructed with a flow channel up to 10-15 inches in diameter. While a device with this great dynamic range would be of little utility as a uroflowmeter, it may have some utility in the civil engineering field for study of open channel flow.

Other Applications

Since the basic mode of operation of the transducer transformer is as a two-phase analyzer, i.e., sensing the proportion of two components (air and fluid), rather than actually sensing flow rate, several related measurements are suggested.

It should matter little whether or not air is mixed with the fluid or the fluid merely displaces the air to form a definable boundary. Thus a device could be constructed which should be of significant value in the study of "white flow" encountered in construction of dam runways and turbine generators. The device could be made to be very sensitive to air bubbles present in a stream which filled the transformer core. Similarly, by injecting a known amount of air into a pipe containing a flowing liquid, one could measure the flow of liquids in a filled pipe under pressure after a suitable calibration is performed.

Analysis of two-phase compositions, salinity, etc., could readily be accomplished using a transducer transformer arrangement as used in the instrument described in this thesis. It is doubtful, however, that this type of instrument could compete with commercial salinometers which have an accuracy of 0.003 per cent but qualitative checks and comparisons could be made which would perhaps be appropriate for many commercial situations.

Conversion of the present instrument--without modification--to a pluviometer is possible; a pluviometer is an instrument for measuring rainfall. A solid-state version could easily be constructed to turn on at the start of a rain shower and plot almost any information regarding rainfall characteristics that one could desire. Since experience has shown the device can easily be designed for extreme sensitivity to low flow rates, this would be an easily implemented application.

It is quite possible that many other applications could be envisioned.

BIBLIOGRAPHY

1. D. J. Gleason, J. K. Lattimer, "The Pressure-Flow Study: A Method of Measuring Bladder Flow Resistance," Journal of Urology, Vol. 87, No. 6, June 1962.

2. B. H. Stewart, "Clinical Experience with the Uroflowmeter," J. Urology, Vol. 84, 1960, pp 414-419.

3. W. M. Drake, Jr., "The Uroflowmeter: An Aid to the Study of the Lower Urinary Tract," J. Urology, Vol. 59, 1948, p 650.

4. E. G. Ballenger, O. F. Elder and H. P. MacDonald, "Voiding Distance Decrease as Important Early Symptom of Prostatic Obstruction," Southern Medical Journal, Vol. 25, 1932, p 863.

5. R. Scott, Jr. and J. S. McIlhaney, "Voiding Rates in Normal Adults," J. Urology, Vol. 85, 1961, p 980.

6. R. Scott, Jr. and J. S. McIlhaney, "Voiding Rates in Normal Male Children," J. Urology, Vol 82, 1959, p 224.

7. D. M. Davis and P. Zimskind, "Progress in Urodynamics," J. Urology, Vol. 87, 1962, p 243.

8. W. M. Drake, Jr., "The Uroflowmeter in the Study of Bladder Neck Obstructions," Journal of the American Medical Association, Vol. 156, 1954, p 1079.

9. W. P. Peter and W. M. Drake, Jr., "Uroflowmetric Observations in Gynecologic Patients," J.A.M.A., Vol. 166, 1958, p 721.

10. J. J. Kaufman, "A New Recording Uroflowmeter: A Simple Automatic Device for Measuring Voiding Velocity," J. Urology, Vol. 78, 1957, p 190.

11. B. von Garrelts, "Micturition in the Normal Male," Acta Chirurgica Scandinavia, Vol. 114, 1957, p 197.

12. B. von Garrelts, "Analysis of Micturition: A New Method of Recording the Voiding of the Bladder," Acta Chirurgica Scandinavia, Vol. 112, 1956, p 326.

13. D. Cardus, E. M. Quesada and F. B. Scott, "Use of Electromagnetic Flowmeter for Urine Flow Measurements," Journal of Applied Physiology, Vol. 18, 1963, p 845.

14. R. P. Lyons and D. R. Smith, "Distal Urethral Stenosis," J. Urology, Vol. 89, No. 3, March 1963.

15. S. Sigmatu, "Uber das Urinogram," Hihu-to-Hitunyo, Vol. 8, 1940, p 42.

16. R. Scott and J. S. McIlhaney, "The Voiding Rates in Normal Male Children," J. Urology, Vol. 82, 1959, p 224.

17. H. H. Holm, "A Uroflowmeter and a Method for Combined Pressure and Flow Measurement," J. Urology, Vol. 88, 1962, p 318.

18. A. K. Oppenheim and E. G. Chilton, "Pulsating-flow Measurement - A Literature Survey," Transactions of the American Society of Mechanical Engineers, 1955, p 231.

19. Robert Sier, "Mass Flow Measurements," Instruments and Control Systems, Vol. 33, June 1960, p 966.

20. T. R. Olive and S. Danatos, "Guide to Process Instrument Elements," Chemical Engineering, June 1957.

21. J. Millman and H. Taub, Pulse and Digital Circuits, p 41, McGraw-Hill Book Company, Inc., New York, 1956.

22. R. Landee, D. Davis and A. Albrecht, Electronic Designer's Handbook, McGraw-Hill Book Company, Inc., New York, 1957.

23. Radiotron Designer's Handbook, Wireless Press (Radio Corporation of America), p 791, 1953.

24. C. W. Quinn, The BRC Notebook, No. 28, Boonton Radio Corporation, Boonton, New Jersey, Spring, 1961.